USAAVLABS TECHNICAL REPORT 66-19

A FEASIBILITY STUDY FOR AIRDROP DELIVERY SIMULATOR

By

R. G. Smethers

F. H. Stokes

March 1966

U. S. ARMY AVIATION MATERIEL LABORATORIES

FORT EUSTIS, VIRGINIA

CONTRACT DA 44-177-AMC-260(T)

THE LOCKHEED-GEORGIA COMPANY
(A DIVISION OF LOCKHEED AIRCRAFT CORPORATION)
MARIETTA, GEORGIA

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DEPARTMENT OF THE ARMY
U. S. ARMY AVIATION MATERIEL LABORATORIES
FORT EUSTIS, VIRGINIA 23604

The technical analysis reported herein was sponsored by the U. S. Army Aviation Materiel Laboratories in an effort to determine the feasibility of developing a device capable of simulating the response of Army-type aircraft resulting from in-flight delivery of cargo by aerial delivery systems.

This command concurs in the conclusions made herein.

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A FEASIBILITY STUDY FOR AIRDROP DELIVERY SIMULATOR

ER 8091

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R. G. Smethers

F. H. Stokes

Prepared by

The Lockheed-Georgia Company
(A Division of Lockheed Aircraft Corporation)
Marietta, Georgia

for

U.S. ARMY AVIATION MATERIEL LABORATORIES
FORT EUSTIS, VIRGINIA

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ABSTRACT

The contractor has performed investigations, research, and engineering for the purpose of ascertaining the technical feasibility of a laboratory apparatus capable of simulating the response of an airplane to an airdrop. The airplanes considered encompass those currently in use by the U. S. Army as well as those projected into the 1975 time period. Airdrops by means of aft extraction, gravity drop, and forced downward ejection were included in the analysis.

The work was accomplished in three phases of investigation:

- Phase I — Analysis of System Requirements
- Phase II — Mathematical Analysis and Modeling
- Phase III — System Conceptual Design

Results of the various phases have led to the conclusion that a simulator is feasible but that no specifically applicable apparatus exists which is capable of performing adequate simulations without considerable modification. The results have indicated those parameters in, and as a result of, an airdrop which must be included in a simulation device. It is additionally concluded that the most practical device which best meets the criteria and system requirements established for a simulator is an analog computer. Although a digital computer could perform as a simulator, it would have the disadvantage of not providing direct reading time histories as would an analog device. Finally, it is concluded that the computer available at USAAVLABS is capable of performing adequate simulations.

FOREWORD

Contract DA 44-177-AMC-260(T) between the U. S. Army Aviation Materiel Laboratories (USAAVLABS) and the Lockheed-Georgia Company provides for a three-phase feasibility study of an airdrop delivery simulator. The project engineer for (USAAVLABS) is R. E. Lane.

At the Lockheed-Georgia Company, completion of this phase of the contract is the responsibility of the Advanced Concepts Department, R. H. Lange, Manager. The Project Leader is R. G. Smethers. The Systems Analysis was performed by F. H. Stokes.

This document is the final report, which is submitted in accordance with the Plan of Performance and for the purpose of fulfilling the terms of the above contract.

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ILLUSTRATIONS

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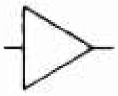
SYMBOLS

α_{FRL}	Angle of attack, degrees
α_g	Angle of attack due to gust, degrees
$\bar{c}$	Mean aerodynamic chord, feet
C_D	Drag coefficient, D/qS
C_L	Lift coefficient, L/qS
C_m	Pitching moment coefficient, M/qSc
c.g.	Center of gravity
D, $f(\alpha_{FRL})$	Airplane drag as a function of angle of attack, pounds
δ_e	Elevator deflection, degrees
δ_F	Flap deflection, degrees
ϵ	Airplane downwash angle, degrees
F_p	Cargo floor force due to cargo, pounds
$F_{X,Z}$	Summation of all aerodynamic forces in the X and Z directions, respectively, pounds
γ	Flight path angle, degrees
g	Acceleration due to gravity, feet/second^2
I_{y_a}	Airplane moment of inertia in pitch, slug-feet^2
i_T	Horizontal-tail incidence angle, degrees
L, $f(\alpha_{FRL}, \delta_e, i_T)$	Lift as a function of angle of attack, elevator deflection, and horizontal-tail incidence angle, pounds
L_{δ_e}	Rate of change in lift with elevator deflection, pounds/degree

ℓ_T	Horizontal-tail length, feet
$M, f(\delta_e, i_T)$	Pitching moment as a function of elevator deflection and horizontal-tail incidence angle, foot-pounds
M_c	Pitching moment due to cargo, foot-pounds
m_a	Airplane mass, slugs
m_c	Cargo mass, slugs
$M_{a.c.}, f(\alpha_{FRL})$	Aerodynamic pitching moment as a function of angle of attack, foot-pounds
$M_{\dot{\alpha}}$	Angle-of-attack damping, foot-pounds/radian/second
M_{δ_e}	Rate of change in pitching moment with elevator deflection, foot-pounds/degree
$M_{\dot{\theta}}$	Pitch damping, foot-pounds/radian/second
q	Dynamic pressure, pounds per foot^2
S	Airplane wing area, feet^2
$\Sigma M_{c.g.}$	Summation of all aerodynamic pitching moments about airplane center of gravity, foot-pounds
T	Airplane thrust, pounds
t	Time, seconds
T_c	Thrust coefficient, T/qS
T_1	Extraction cable force, pounds
θ	Airplane pitch angle, degrees
U	Airplane forward speed, knots
W_a	Airplane weight, pounds
x_c	Distance of cargo center of gravity from airplane center of gravity, feet
γ_e	Perpendicular distance from thrust line to center of gravity of airplane, feet



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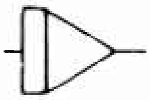

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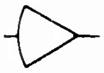

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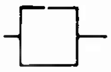

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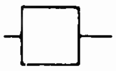

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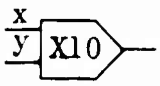

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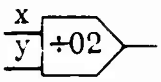
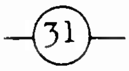


Divider x/y



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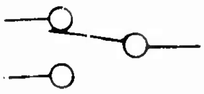

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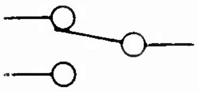

Manual switch

Solid state diode

A dot over a symbol indicates first derivative of that quantity with respect to time. Two dots over a symbol indicates second derivative of that quantity.

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INTRODUCTION

This report presents the results of a technical study to determine the feasibility of developing a laboratory device capable of simulating the response of Army-type aircraft resulting from the in-flight delivery of cargo by various aerial delivery systems. The study was performed in three phases:

- o Phase I — Analysis of System Requirements
- o Phase II — Mathematical Analysis and Modeling
- o Phase III — System Conceptual Design

The primary purpose of the Phase I portion of the study was to define and establish the system requirements for a simulator. This phase, in turn, was subdivided into the following studies:

- o Technology Survey
- o Establishment of Equations of Motion
- o Parametric Analysis of Terms
- o Literature and Patent Search

A survey of technology was conducted in order to determine the effects of current and projected airdrop techniques on the system requirements for simulation of airplane response and airload characteristics. The airdrop techniques included altitude drop, tethered systems, and low-level extraction. The survey included consideration of the complete airplane system with respect to the effects on aerodynamics, loads, and maneuvers resulting from airdrop cycles. The ground handling and loading of cargo and cargo retention forces for crash requirements were also included in this phase.

The airplane equations of motion for 3 degrees of longitudinal freedom were also established during Phase I. The analysis of these equations resulted in the establishment of parameters to be considered in the Phase II mathematical analysis of an airdrop simulator.

A literature and patent search, summarized in the appendix (Page 119), revealed that the only likely device already in existence which could be adapted for use as a simulator is the Princeton Dynamic Model Track located at Princeton University. The patent search did not reveal any related items applicable to this study.

The primary purpose of the Phase II portion of the study was to develop a mathematical model for analyzing the results of Phase I. Results derived from the Phase II mathematical analysis were, in turn, parametrically analyzed to determine those factors which had sufficient criticality or significance to be included in the Phase III conceptual design. Phase II was performed in two steps, as follows:

- o Development of mathematical model for analog computer
- o Criticality analysis of parameters

The development of the analog computer program required the input of aerodynamic data for current cargo-type aircraft. The existing aerodynamic data for the C-130E were used for this required computer input and were considered typical of current cargo aircraft. The analog computer was then used to derive time histories of airplane response resulting from various cargo delivery systems.

The symbolic representation of the equations of motion, the analog computer wiring diagrams, and a tabulation of the computer runs are presented in this report. Sample time histories of the computer results, depicting the airplane's response to various forcing parameters, are presented to permit comparison and visual analysis of the relative influences.

Analog computer results were analyzed for criticality of parameters, and the discussion is supplemented by cross plots of the time histories. The analysis is concluded with recommendations for candidate parameters to be included in the conceptual design of an airdrop simulator.

The primary purpose of the Phase III portion of the study was to give consideration to concepts for the form of the simulator based upon the results of Phase II. In order to establish the conceptual system design, the following factors were considered in the approach taken:

- o Criteria and design considerations for simulator
- o Concepts for airdrop simulator
- o Application of criteria to concepts
- o Analysis of selected conceptual designs

Phase III was devoted to the conceptual design of a simulator by the utilization of the requirements established and analyzed in the previous phases. Criteria and design considerations were established

in terms of cost, accuracy, simplicity, compatibility with existing airplane systems, reliability, adaptability to future systems, utility in terms of additional uses, and productivity. Candidate concepts were grouped into three categories:

- Mechanical
- Electromechanical
- Electronic

The criteria were applied to concepts in each category, and an evaluation was made of the concept's potential and practicability as a simulator. The rating of the various concepts indicated that three concepts could serve as an airdrop simulator:

- Dynamic Model Track, Princeton University
- Analog Computer
- Digital Computer

Of these three, the analog computer is considered to be the best simulator because of its ability to produce time histories of airplane response rapidly and accurately. The digital computer produces the same data and is considered to be next best because the direct machine output must be converted from a printed readout into plotted time histories by some form of plotting machine. The Princeton facility is ranked third because it involves the use of models, with inherent scaling effects and problems, and because it requires several months of preparation and calibration for each system to be simulated. In addition, it is estimated to be the most costly to operate.

While the analog computer is considered to be the best simulator, the digital computer facility at USAAVLABS is capable of performing as an airdrop simulator. Time histories can be produced by using the existing X-Y plotting machine at USAAVLABS. The time required to produce a single simulation is on the order of 10 minutes of computer time plus 20 minutes of plotting time. If this facility were used, about 35 weeks of time would be required to investigate the apparent backlog of desired simulations.

PHASE I - ANALYSIS OF SYSTEM REQUIREMENTS

The primary purpose of the Phase I portion of the study was to define and establish the system requirements for a simulator. This phase, in turn, was subdivided into the following studies:

- Technology Survey
- Establishment of Equations of Motion
- Parametric Analysis of Terms
- Literature and Patent Search

TECHNOLOGY SURVEY

A technology survey has been made of the current and projected aerial delivery concepts in order to determine their influence on airplane response. Basically, the airdrop systems can be divided into three categories:

- Altitude drop
- Tethered system
- Low-level extraction

Each system, as well as the applied forces present during the airdrop cycle, will be discussed separately.

Airdrop Systems

Altitude Drop

Altitude parachute drops are made from an altitude of 1200-1500 feet, and one of the three following basic methods of cargo extraction is used:

- Aft parachute extraction
- Aft gravity extraction
- Forced aft ejection
- Forced downward ejection

Aft Parachute Extraction - This method of cargo delivery presumes to be in level flight with the cargo pulled from the airplane by an extraction parachute. The drag of the deployed parachute provides the extraction force and acceleration which are functions of airspeed and parachute type and diameter. As the cargo moves aft in the airplane, there is an aft shift in center of gravity which increases in magnitude until the cargo tips off the lip of the ramp or fuselage. The aft shift, in relation to the lift and aerodynamic pitching moment of the airplane, causes an increase in angle of attack accompanied by a nose-up pitching moment. The sudden loss in weight as the cargo leaves the airplane produces an instantaneous reversion to normal center of gravity limits plus a sudden amount of excess lift. These two factors produce a translation along the vertical axis and an aerodynamic nose-down pitching moment. The result is manifested in an incremental load factor (known as "g" jump) proportional to the amount of excess lift, and in a longitudinal "short-period" type of motion. The amount of pilot input, if any, to be employed during this maneuver is a function of the speed with which the cargo leaves the airplane, its relative weight, and the damping characteristics of the airplane. A typical airplane response, as measured in flight tests, is illustrated by Figure 1.

The dropping of cargo from altitudes of 1500 feet permits multiple drops or deliveries from the same airplane. This is known as recycling. Recycling time can be an important parameter in terms of its effect on aerodynamics from the standpoint of being too short or too long. If the time is too short, the disturbance to the airplane caused by the previous extraction may be amplified by the next extraction. This could cause a "resonant" condition which may reach limits beyond the stability of the airplane or the control of the pilot.

Structural loads are the result of the airplane's maneuver and the inherent aerodynamic parameters involved in stability and controllability. Accordingly, the maneuver condition described previously produces structural loads which are a time variable throughout the extraction period. The pitching maneuver and accompanying increase in angle of attack cause an increase in wing loads with attendant increases in wing shear, bending moment, and torsion.

These higher wing loads must be balanced, in most cases, by higher down loads on the horizontal tail which induce higher loads in the aft fuselage. The incremental load factor caused by the sudden excess lift produces the same effect which is additive to the condition already described. Accordingly, the delivery process must be arranged so that the total incremental load factor does not exceed the design maneuver load factor for the airplane.

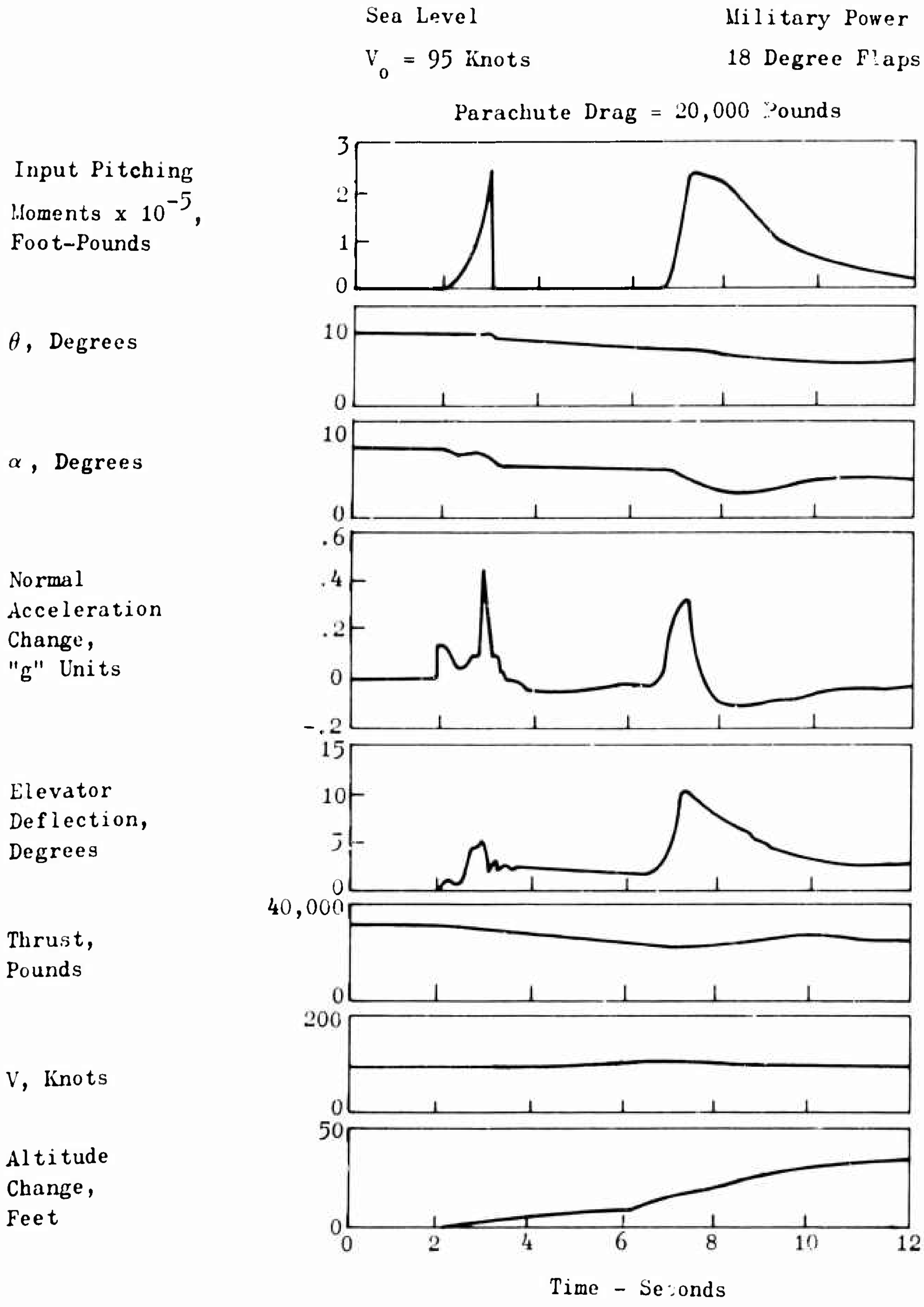


Figure 1 - Aircraft Response to Cargo Extraction

If the maneuver is conducted at low speeds, and such is usually the case, the pitching motions may produce an angle of attack sufficient to stall the airplane. To preclude such a situation, the delivery may be performed with partial flap deflection. However, the structural design requirements established by Reference 1 only require design for a maneuver load factor of 2.0 with flaps deflected. Hence, the maneuver resulting from delivery must account for this factor.

The criteria of Reference 1 also require the airplane to be designed for a pitching velocity and pitching acceleration which are usually determined from a specified stick motion as a function of time. The designer of the airplane also has the option to choose a specified arbitrary set of values which are presumed to envelope those which the airplane is likely to ever attain in its service history. Accordingly, the maneuver resulting from delivery of cargo must not exceed the design values for the airplane.

Airplanes are structurally designed for maneuver by pilot-imposed motions as well as those loadings imposed by turbulence or gust conditions. With few exceptions, airplanes are not required to be designed for a condition which presumes the pilot to be performing a maneuver while encountering a gust at the same time. Practically, however, the delivery of a cargo package under absolute calm conditions is impossible, and so the "g" jump could very likely be magnified by the occurrence of a simultaneous gust. The combined loads should not exceed the design maneuver strength of the airplane.

Aft Gravity Extraction - The success of this method of aerial delivery depends, for the most part, upon pilot proficiency. The extraction cycle consists of flying the airplane nose high at constant altitude so that gravity will accelerate the package aft and out of the airplane upon release of the cargo restraint. The use of excess engine power may also be used to accelerate the cargo from the airplane. A parachute subsequently deploys which decreases the vertical velocity of the cargo to inhibit ground impact damage. As the cargo is released and begins its travel aft, the previously discussed center-of-gravity travel and pitching moments develop which tend to stall the already nose-high airplane. Throughout the gravity extraction, the pilot must use power and longitudinal control to prevent the airplane from stalling. Once the cargo clears the airplane, there is an excess of lift due to the loss in weight, and the pilot must take corrective action to minimize airplane response and "g" jump.

Forced Aft Ejection - Cargo can be ejected in an aft direction by means of explosive charges, springs, or other energy storing devices. Inasmuch as the ejection force acts in the horizontal or X plane, the reaction imparted to the airplane also acts in the X plane. The immediate effect on the response of the airplane to the horizontal acceleration is an increase in forward velocity. The increase in

velocity, in turn, results in increased lift and pitching moment, both of which must be countered by pilot response as a function of the degree of control available and the rapidity with which pilot response can be applied. In addition, a mild pitch-up might occur if the ejecting force were applied relatively far below the vertical position of the center of gravity.

The effect on structure of forced aft ejection would be manifested in the loads resulting from the motions described in the previous paragraph. Again, design load factors and pitching velocities and accelerations should not be exceeded. In addition, the horizontal acceleration, or reaction, imparted by ejection would immediately be reacted by the structure restraining or retaining the ejection device. Some assumption would have to be made in regard to the structural integrity of the fuselage frame, bulkhead, or flooring involved. It is emphasized, however, that the horizontal acceleration should at no time be permitted to exceed the maximum for which the basic airframe was originally designed in accordance with the conditions specified by the MIL-A-8860 series of structural design specifications.

Forced Downward Ejection - Dropable cargo mounted in a "bomb bay" or under the airplane can be ejected by gravity or forced downward by a charge of stored energy. Such cargo compartments, or pylons, are normally located at or near the center of gravity. Hence, the downward ejection usually results in only vertical translation or "g" jump. Structurally, however, the airplane must also be designed for local reaction due to the forcing device.

Tethered System

Many concepts of aerial delivery using the tethered principle have been devised. All these systems have a common feature as far as airplane reaction is concerned, which is that one end of the cable is always attached to the airplane, hence the name "tethered." Therefore, it is possible to deseribe one extraction cycle that is representative of all. Examples of typical tethered systems are the contractor-developed systems known as the TROLLEY and TRAM shown in Figure 2. Both of these systems utilize the drag parachute concept for ejection.

In the TROLLEY system the airplane tows a drag chute on the end of a 1500-foot cable. The tension in the cable is reflected through a block clamped to the cable immediately behind the trolley. Between the block and the winch in the airplane, the cable has no tension. The trolley is attached to the cargo by means of cables. At the instant of cargo release, the cable tension due to the drag chute ejects the cargo via the block and trolley and the cargo free-falls for a short period as the winch unreels more cable. The winch is braked, which takes about half a second; this thereby stops the cable

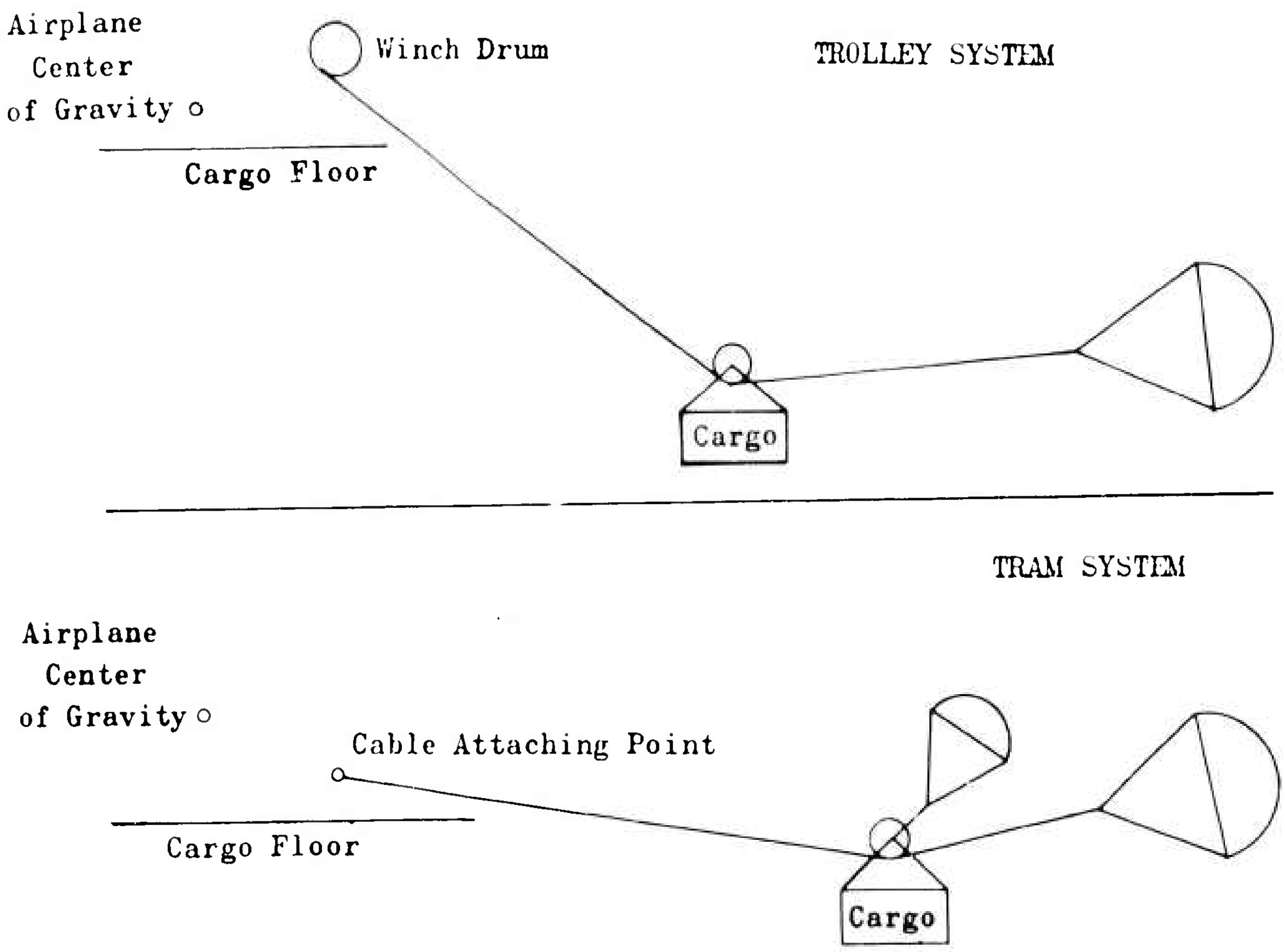


Figure 2 - TROLLEY and TRAM Systems

and causes the trolley to move down the cable toward the drag chute with the cargo. The idea behind this system of aerial delivery is that the cargo drag and the drag chute will slow the cargo enough so that, upon impact with the ground, the horizontal and vertical velocities will be close to or near zero.

In the TRAM system the airplane tows a drag chute also, but the cable is attached directly to the airplane and the cargo is ejected by means of an auxiliary drag chute. Once the cargo is out of the airplane, it slides down the cable by a trolley, and the auxiliary drag chute acts as a lifting and dragging device on the cargo to slow the horizontal and vertical components.

These delivery systems cause changes in the airplane lift, drag, and pitching moments similar to those previously described. This unbalance of forces and moments results in accelerations and altitude changes which must be controlled through use of pilot input or elevation deflection. The essential difference between the two delivery systems, as far as the flight characteristics are concerned, is the relative amount of change in lift, drag, and pitching moment that occurs in the process of delivery. Structurally, the delivery process causes loads through the winch to the basic structure of the airplane. Depending upon the airplane used, the analyses of forces shown by Figure 2 enable provision for adequate local strength.

The forces and moments about the airplane center of gravity vary according to the angle of action of the cable attached to the airplane which is, in turn, a function of the location of the cargo. Time of the extraction is also an important factor on airplane forces and moments. The extraction cycle begins in level flight while towing a parachute on the end of a long cable.

<u>Low-Level Extraction</u>

Low-level extraction (LOLEX) systems are basically of two types. One system is characterized by cargo extraction by parachute while flying in the proximity of the ground, while the other system extracts the cargo by ground-based pendant cables. Both systems may be used when the airplane landing gear is either on or off the ground.

<u>Low-Level Parachute Extraction</u> - There exist several methods by which cargo is extracted while flying in close proximity to the ground. The low-altitude parachute extraction system (LAPES) begins with the airplane's flying straight and level at an altitude between 5 and 15 feet above the ground. It is optional whether or not the parachute is deployed before or after level flight is attained. Upon release, the cargo is extracted by the parachute at an acceleration proportional to the airspeed and parachute diameter. The nose-up pitching moment caused by the aft movement of the cargo will result in a flight path

change, the magnitude of which is directly dependent upon the cargo acceleration. Upon initiation of cargo extraction, the resultant maneuver of the airplane must be carefully monitored by the pilot to prevent excessive load factor as well as to preclude damage to the aft end of the cargo door by contact with the ground due to aircraft rotation. The cargo tip-off characteristics at the aft end of the cargo door have a bearing upon the aircraft maneuver and depend to a great extent upon the cargo size and density.

Figure 3 is illustrative of the C-130 response to a low-fly-by extraction of cargo and is typical of the time histories of some of the parameters influencing structural loads which result from these analyses. The parameters recorded on the figure are as follows:

α Angle of attack,

θ pitch angle,

δ elevator deflection,

U airspeed,

Δ change in normal acceleration from 1.0 g flight,

γ flight path angle, and

M_c input moment caused by the extraction of cargo.

The parachute low altitude delivery system (PLADS) requires that the airplane maintain a constant 200-foot altitude over the drop area as well as a constant airspeed. The extraction parachute is deployed in a reefed condition while the cargo is restrained in the airplane. When the drop point is reached, the parachute is unreefed and extraction occurs. The cargo package then swings through a 90-degree arc timed so that ground contact occurs at the bottom of this arc. The airplane reaction will be somewhat similar to that of LAPES except that aerodynamic ground effects will not be as great.

Ground-Based Extraction - This delivery system depends upon ground-based equipment which extracts the cargo and arrests its airplane-induced forward velocity. A pendant cable is stretched across the delivery flight path and each end is fastened to a nylon tape wound around the drum of an energy absorption device. A tail hook, attached to the cargo, engages a ground cable as the airplane passes over. The cargo is extracted by engagement of the pendant and the retardation effect of the energy absorbers. The resulting airplane maneuver is much like that of the other low-level extraction systems.

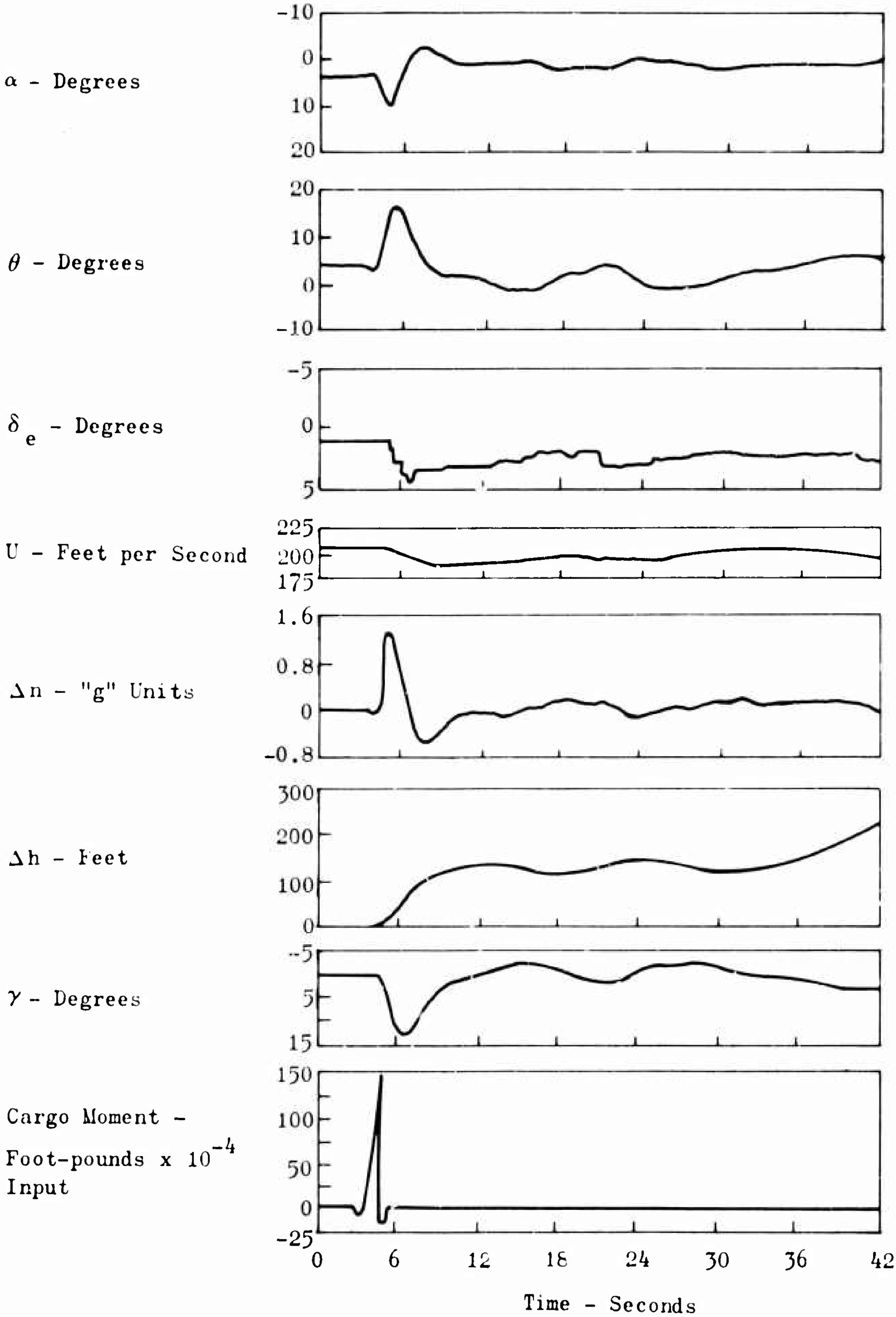


Figure 3 - C-130B Cargo Extraction Time History

Applied Forces

The forces applied to the airplane that result from ground loading, from the retention of the cargo in the airplane, and from airdrop have a very definite bearing on the design of the cargo floor structure. The MIL-S-8860 series of specifications is generally used throughout industry as a basis for structural design of military aircraft. Reference 2 presents the loads and restraint factors used in the analysis of these loadings.

Ground Loading

Cargo compartment flooring is designed in accordance with military specifications to withstand 1,000 complete trips in a fixed-path of a steel wheel 8 inches in diameter with a rim 2 1/2 inches wide under a 1,000-pound load. It must survive the environment without undue surface wear or evidence of fatigue. Floor strength is affected primarily by flight loads. Specifications of Reference 2 require the limit floor pressures to be 75 n_z pounds per square foot (PSF) for personnel floor, 100 n_z PSF for low-density cargo areas, and 300 n_z PSF for all other cargo areas, where n_z is the maximum design symmetrical flight limit load factor. This factor may be either maneuver or gust, whichever is higher. The total load in pounds in any particular area, however, is determined by pertinent weight and balance limitations.

Crash Load Retention Forces

Reference 2 provides the source of design requirements listed in the following. The longitudinal load factor is directed in all forward azimuths within 20 degrees from the longitudinal axis. The vertical load factor is directed downward, normal to the longitudinal axis, and equal to one-half of the longitudinal values. The specified load factors act separately. For cargo other than aerial delivery equipment, the following minimum crash load factors, acting separately, are:

Longitudinal	8.0 forward, 1.5 aft
Lateral	1.5 to right and to left
Vertical	4.5 down, 2.0 up

The aerial delivery restraint load factors in the military specifications are considered for non-crash configurations only. Therefore, the following minimum load factors acting separately shall apply to aerial delivery load and equipment:

Longitudinal	4.0 forward, 1.5 aft
Lateral	1.5 to right and to left
Vertical	4.5 down, 2.0 up

ESTABLISHMENT OF EQUATIONS OF MOTION

The equations of motion of the airplane are derived for 3 degrees of freedom. It is considered that 3 degrees of freedom are sufficient based on the assumption, reasonably borne out by practice, that the airplane performs cargo drops and deliveries in straight and wing-level flight. Since most extractions and drops are from the fuselage it is unnecessary to consider roll or lateral terms. Accordingly, all force and moment terms due to yaw angle, yawing velocity or acceleration and bank angle, and rolling velocity or acceleration are excluded from the equations. On the basis of experience, the inertial coupling terms are also omitted from the equations. It is considered doubtful that cargo airplanes will achieve an interrelation of the moments of inertia about the three primary axes, as fighter aircraft have, which would make inertia coupling of significance.

The airplane is free to translate along the longitudinal (X) and vertical (Z) axis and to rotate or pitch about the (Y) axis. An orthogonal system of stability axes has been used inasmuch as aerodynamic data are most frequently presented in this system. The axis system is shown in Figure 4.

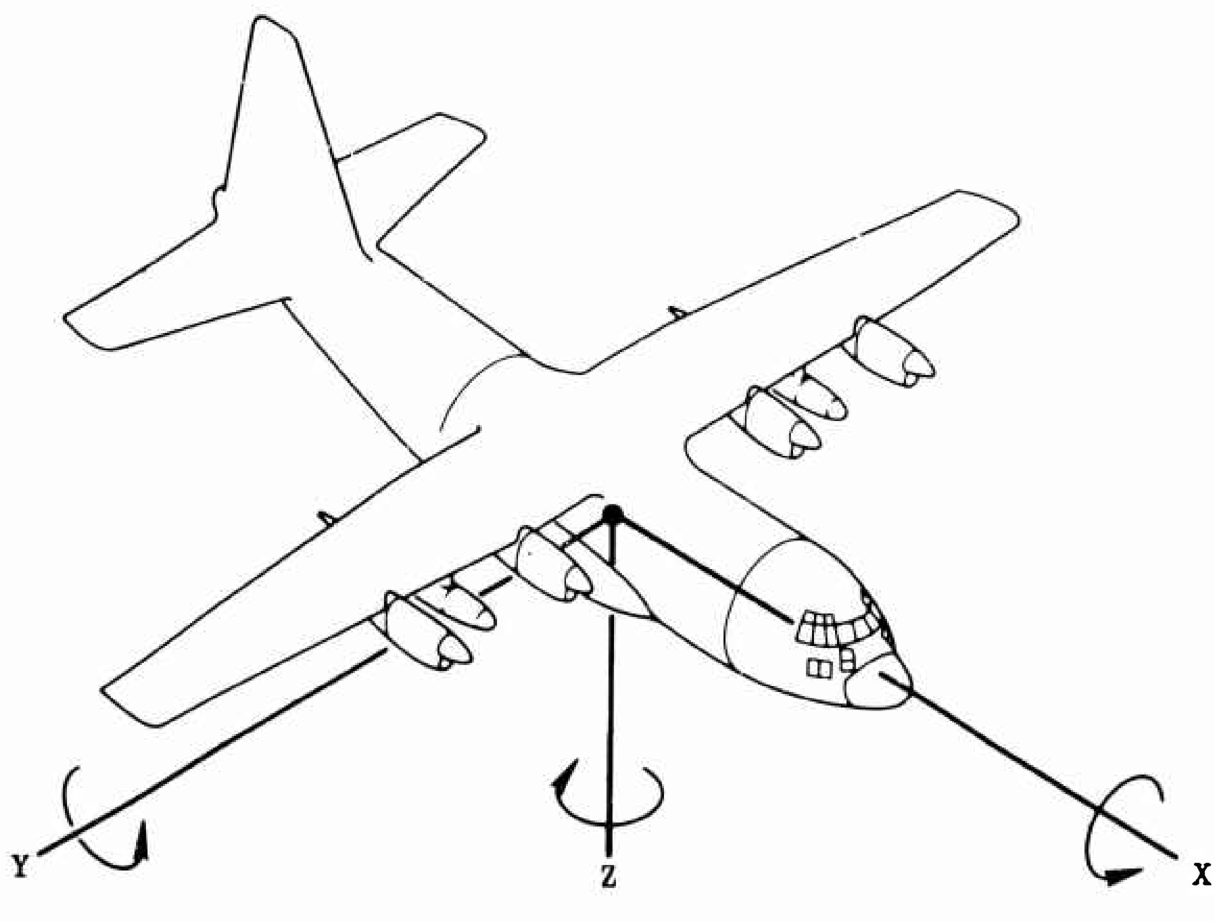


Figure 4 - Airplane Orthogonal Axis System

Inasmuch as this study is restricted to longitudinal or pitching moments, the forces and moments can perhaps best be described by a two-dimensional display as shown by Figure 5.

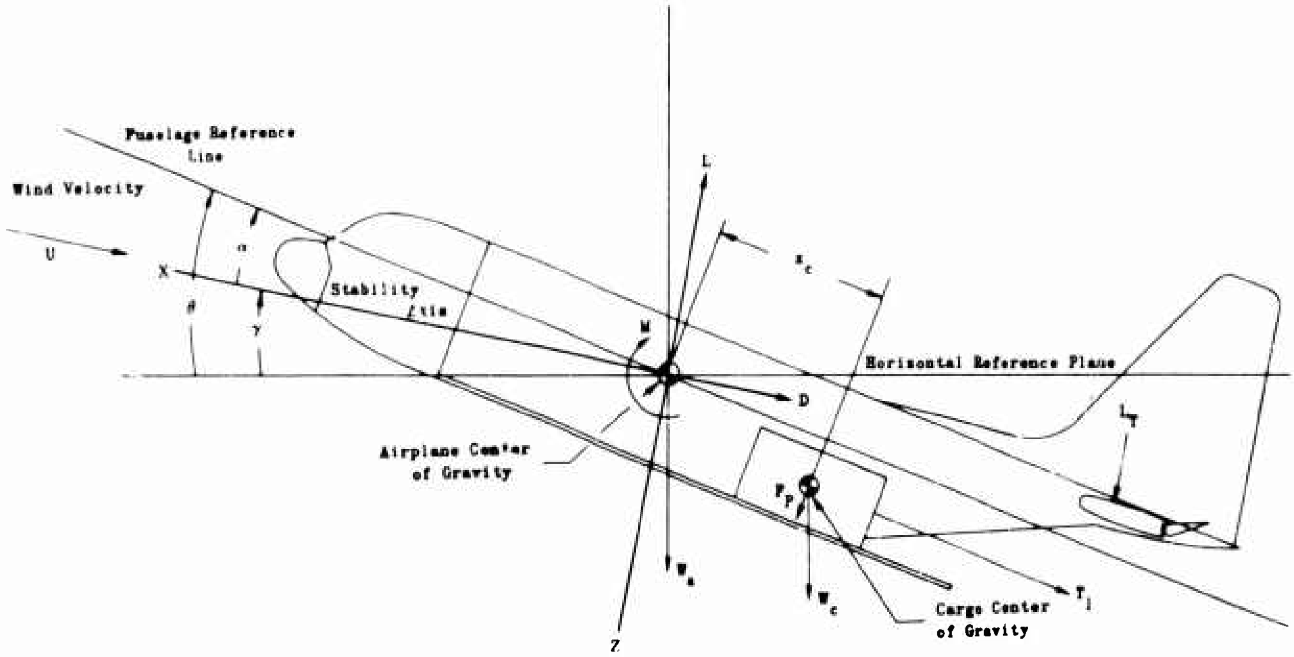


Figure 5 - Stability Axis System

For illustrative purposes, the airplane has been placed at an exaggerated angle of attack. Positive directions of the axis system from the center of gravity, as shown by Figure 4, are as follows: Forward - toward X, downward - toward Z, and nose-up pitching moment - toward M. The angles are positive as shown by arrowheads.

Summing forces along the X-axis,

$$\Sigma F_X = m \overset{o}{U}.$$

Expanding into aerodynamic terms yields

$$\Sigma F_X = T \cos \alpha_{FRL} - W_a \sin \gamma - D, f(\alpha_{FRL}) + F_{\bar{X}}$$

where

$$F_{\bar{X}} = - F_p \sin \alpha_{FRL} - T_1 \cos \alpha_{FRL}$$

The complete equation used for simulation is then

$$m_a \overset{o}{U} = T \cos \alpha_{FRL} - W_a \sin \gamma - C_D, f(\alpha_{FRL}) qS - F_P \sin \alpha_{FRL}$$

$$- T_1 \cos \alpha_{FRL} . \tag{1}$$

The scaled equations are explained in the Phase II section of this report.

Summing forces along the Z-axis,

$$F_Z = - mU\dot{\gamma}$$

Expanding into aerodynamic terms yields

$$\Sigma F_Z = - T \sin \alpha_{FRL} + W_a \cos \gamma - L, f(\alpha_{FRL}, \delta_e, i_T) + F_{\bar{Z}}$$

where

$$F_{\bar{Z}} = - F_P \cos \alpha_{FRL} .$$

The complete equation used for simulation is then

$$- m_a U\dot{\gamma} = - T \sin \alpha_{FRL} + W_a \cos \gamma - L, f(\alpha_{FRL}, \delta_e, i_T)$$

$$- F_P \cos \alpha_{FRL}. \tag{2}$$

This equation, scaled for simulation, is given in the Phase II section of this report.

Summing moments about the center of gravity in the X-Z symmetrical plane through which pass the Y-axis perpendicular to this plane,

$$\Sigma M_{c.g.} = I\ddot{\theta} .$$

Expanding into aerodynamic terms yields

$$\Sigma M_{c.g.} = M_{a.c.}, f(\alpha_{FRL}) + M_{\dot{\theta}} \dot{\theta} + M_{\dot{\alpha}} \dot{\alpha} + M, f(\delta_e, i_T) + M_{\overline{c.g.}}$$

where

$$M_{\overline{c.g.}} = F_P \left(x_c - x_{c.g.}\right) .$$

The complete equation used for simulation is

$$I_y \ddot{\theta} = M_{a.c.}, \; f(\alpha_{FRL}) + M_{\dot{\theta}} \dot{\theta} + M_{\dot{\alpha}} \dot{\alpha} + M, \; f(\delta_e, i_T) + F_P \left(x_c - x_{c.g.}\right). \tag{3}$$

This equation, scaled for simulation, is given in the Phase II section of this report.

These three equations are presented in a manner necessary to achieve the flexibility needed when different airdrop delivery systems are studies. Additional terms may be easily added depending upon the delivery system under consideration.

In regard to the terms in the above equations, all the parameters presented relate either to the airplane or the cargo to be airdropped. The two bodies have been purposely separated to facilitate derivation of auxiliary equations.

The equation that simulates airplane reaction due to cargo movement is written as a summation of platform forces, F_P. This equation is given as follows:

$$F_P = W_c \cos \theta + m_c \; U \dot{\gamma} \cos \; \alpha_{FRL} - m_c \dot{\theta} \dot{x}_c - m_c \left(x_c - x_{c.g.}\right) \ddot{\theta}$$

The equation acknowledges the Coriolis effects caused primarily by the aft movement of the cargo. This effect has been found to be of significance in previous contractor studies.

<u>Auxiliary Equations</u>

The longitudinal equations of motion as presented above describe the airplane response, but the auxiliary equations describe the functions that upset the natural balance attained in straight and level flying. For this analysis the necessary forcing functions are the tip-off phenomenon, vertical gust, and cargo extraction acceleration.

<u>Tip-Off Phenomenon</u> - The tip-off phenomenon is described as the mathematical representation of the decrease in cargo floor load as the airdrop package passes the ramp door lip. The cargo package is considered to be a point mass acting as its own center of gravity. The rearward travel of this mass causes nose-up pitching moments about the airplane center of gravity. Theoretically, when this point mass

reaches the lip, the pitching moment becomes zero. This is not the true representation of the physical system, however. Consider the system shown in Figure 6.

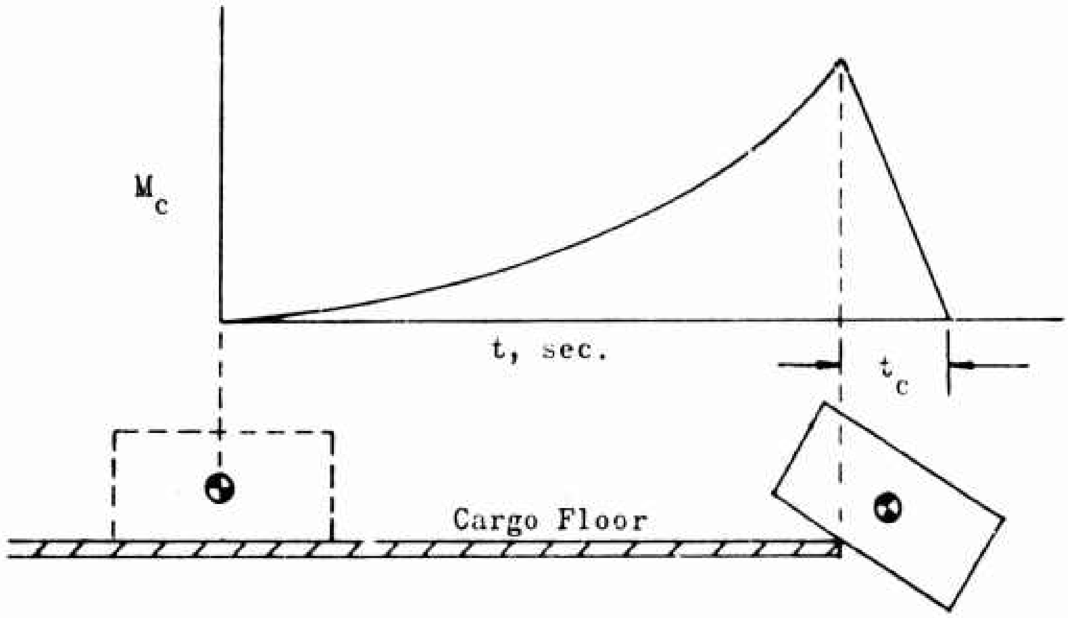


Figure 6 - Tip-Off Phenomenon

The cargo at rest is shown by the dashed block. Pitching moment buildup caused by the aft movement of the cargo reaches a peak as the cargo center of gravity passes the lip. The floor load is assumed to be relieved linearly by the rate of cargo density. For example, if the package weighs 20,000 pounds and has a density of 1000 pounds per foot, then the relieving load will become zero at 10 feet after the cargo center of gravity passes the lip. The accelerating cargo is shown in the tipped position along with a representation of the corresponding input pitching moment. M_c is calculated by

$$M_c = F_P \cdot x_c \text{ and } x_c = \tfrac{1}{2}\ \ddot{x}_c\ t^2 .$$

Vertical Gust - Vertical gust causes abrupt changes in angle of attack. The total felt by the airplane when disturbed by a gust is

$$\alpha_{TOT} = \alpha_{FRL} + \alpha_{gust} .$$

In this study, the gust is assumed to have a (1 - cos) function and the resultant formula for this gust is

$$\alpha_g = \frac{\alpha_{g_{max}}}{2} \left[1 - \cos \frac{2 \pi d}{25 \bar{c}} \right]$$

where

$\alpha_{g_{max}}$ = maximum gust angle of attack and may be expressed as v/U;

v = vertical velocity of a column of air - assumed 25 feet per second for this analysis;

d = distance penetrated into the vertical gust, feet; and

$\bar{c}$ = mean aerodynamic chord of the airplane, feet.

Cargo Extraction Acceleration - The distance that the cargo travels in the airplane in a given amount of time depends directly upon its acceleration. The cargo location in the airplane is computed simply by

$$x_c = \frac{1}{2} \ddot{x}_c t^2$$

where

x_c = distance cargo center of gravity travels in airplane, feet;

$\ddot{x}_c$ = cargo acceleration, feet per second squared; and

t = time, seconds.

In this analysis the cargo acceleration, $\ddot{x}_c$, is given the value of 32.2 feet per second squared unless otherwise stated. This parameter is non-dimensionalized by the cargo weight; i.e., for a 2 g extraction, $\ddot{x}_c$ = 64.4 feet per second squared. An extraction force of twice the cargo weight must be applied to the cargo.

PARAMETRIC ANALYSIS OF TERMS

An analysis has been made of the equations of motion to determine their adequacy and to determine whether all significant parameters have been included. The relative importance of each parameter has been examined through the use of existing analog programs on aerial delivery systems. In the following paragraphs, each equation is presented in order, and the candidate parameters are discussed.

Equation (1)

Equation (1) sums forces along the (X) stability axis and is as follows:

$$m_a \dot{U} = T \cos \alpha_{FRL} - W_a \sin \gamma - C_D, f(\alpha_{FRL}) qS - F_P \sin \alpha_{FRL}$$

$$- T_1 \cos \alpha_{FRL} .$$

Thrust, T - At the beginning of each aerial delivery cycle, the airplane is in trimmed flight with the thrust equal to the drag. If a parachute is being towed for the purpose of extracting the cargo, the thrust must be adequate to overcome the excess drag. The thrust terms in the equation need not normally be a variable in any particular run, except as noted under the paragraph entitled Extraction Cable Force T_1, because past experience has shown that the rate of thrust increase (especially for turboprop and jet engines) is too slow for effective use.

Air Speed, U - The desired goal of the ultimate airdrop simulator is to have the capability of covering a speed range from 60 to 250 knots. This parameter primarily influences the airplane dynamics since slow airspeeds are conducive to stalls. It is important to maintain airspeeds high enough so that parachutes of reasonable diameter may be used to extract the cargo; but at the same time airspeed must be low enough so that the extracted cargo will have a minimum of forward momentum. This parameter is very significant from the standpoint of airplane handling qualities. Generally, airplanes are not too sensitive to airspeeds of this magnitude unless they approach the stall or minimum control speed.

The effect of altitude is directly related to the change in velocity and is measured by the change in the dynamic pressure, q. If airdrop systems which use parachutes are incorporated, an increase in altitude will increase the parachute diameter for the same extraction force due to the decrease in atmospheric density. An increase in altitude will result in an increase of the delivery airspeed for the same gross weight at sea level. Therefore, the cargo has greater momentum at altitude upon extraction. It is very doubtful if altitude can be adequately simulated other than with a computer.

Weight, W - The weight must initially be all inclusive. The total weight of the airplane includes the airplane alone, W_a; plus cargo weight and associated equipment, W_c. Mathematically, this term appears as follows:

$$W = W_a + W_c .$$

The airplane weight, W_a, will always be assumed constant in airdrop analysis. The time span over which the reactions occur is so small that the fuel used will not change the weight significantly. The

separation of the two weights is not significant. Cargo weight has an important effect on the airdrop technique used with any cargo airplane. All airplanes are designed to some maximum payload-range capability, but if a drop capability is incorporated, the airplane structure must be adequate, which may or may not increase the airplane gross weight significantly. This consideration would be necessary in the evaluation of the drop system. The cargo weight range considered in the Phase II study was 3,000 to 20,000 pounds.

Flight Path Angle, γ - The flight path angle γ is described mathematically as follows: $\gamma = \theta - \alpha$. The parameter is a variable and describes the angle which the velocity vector of the airplane makes relative to the horizontal reference as shown in the stability axis system in Figure 5 .

Angle of Attack, α - This parameter is of prime importance for it is the controlling influence on lift, drag, and pitching moment as well as components of weight and extraction forces. As such, it is continuously computed in a computer run in order to provide an input to the lift, drag, and pitching moment functions. It is normally measured with respect to the fuselage reference line, FRL.

Lift, L - The airplane lift varies directly as the square of the forward velocity; it may be calculated by

$$L = C_L \, q \, S$$

where

L = airplane total lift, pounds;

C_L = airplane lift coefficient;

S = wing area, square feet; and

q = dynamic pressure $= \frac{1}{2} \rho U^2$

where

ρ = atmospheric density, slugs per cubic foot; and

U = true airspeed, feet per second.

Drag, D - The drag is that of the airplane alone. It is a function of the airplane angle of attack, and hence lift coefficient, and is a nonlinear parameter. The airplane configuration influences the magnitude of the drag and must therefore be programmed accordingly. Flap deflection, gear position, opened cargo doors, aerodynamic brakes of the airplane, etc. are but a few of the physical changes that alter this quantity.

The remaining term on the left side of the equation, $F_{\bar{X}}$, represents any force or summation thereof that may occur due to the inherent aerial delivery technique. This force may be the forcing function to extract cargo caused by a deployed parachute, a ground hook that has engaged a pendant cable stretched across the drop zone, or a vertical gust.

The initial mass (m) is a summation of the airplane plus cargo and is presented mathematically as follows:

$$m = m_a + m_c$$

As the cargo leaves the airplane the tip-off phenomenon will simulate more accurately the tapering off of the forces and moments as it passes over the end of the ramp door.

<u>Extraction Cable Force, T_1</u> - This term is related to the cargo extraction acceleration, which has been previously discussed, in that it directly influences that portion of the airplane response resulting from the cargo motion. A low force, hence a low acceleration, causes a slower change in center of gravity, a more prolonged tendency to pitch nose-up, and attendant increases in required application of corrective elevator. Conversely, a relatively high force tends to minimize pitching effects. Indeed, in the extreme case, an infinitely high cable force and acceleration would only result in "g" jump caused by the sudden loss in airplane weight.

<u>Ejection Force</u> - It is emphasized that the effect on the airplane of forced aft ejection is covered by Equation (1), by taking the thrust, T, a variable. To account for this ejection force, it is necessary only to program thrust into the computer so that the impulse time history of the ejection force is added to the basic magnitude of the thrust at the time of cargo ejection.

Equation (2)

Equation (2) sums forces along the (Z) stability axis. Some of the terms are similar to those of Equation (1) except that the sin and cos are reversed in corresponding terms. The equation is as follows:

$$\Sigma F_Z = - T \sin \alpha_{FRL} + W \cos \gamma - L, f(\alpha_{FRL}) + L, f(\delta_e) + L, f(i_T)$$

$$+ F_{\bar{Z}} = - mU\dot{\gamma}$$

Lift, L - The L, f(α_{FRL}) term is the complete lift of the airplane as a function of angle of attack and includes all quantities that place the equation in equilibrium when the horizontal incidence and elevator deflection are set to zero. If the airplane under consideration has propellers, the lift terms must be programmed at the proper thrust coefficient. For adequate representation, provision is made so that this term can be programmed in a nonlinear fashion to account for stall. The lift is computed by the following formula:

$$L, f(\alpha_{FRL}) = C_L, f(\alpha_{FRL})\, q\, S$$

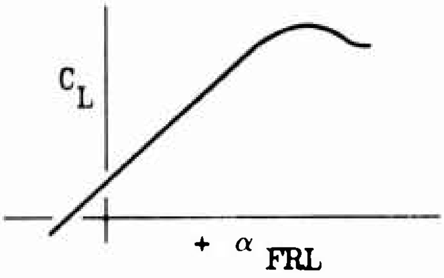
For equilibrium along any straight unaccelerated flight path, the lift is equal to the weight. Therefore, the lift coefficient may be calculated by

$$C_L = \frac{L = W}{qS}$$

For accelerated flight the lift becomes

$$L = nW$$

where n is the normal acceleration along the (Z) axis. The lift coefficient as a function of angle of attack appears, in general, as follows:



When solving the equations of motion by the analog computer, the C_L vs α_{FRL} is programmed on a function generator for continuous computation.

Lift due to Elevator - The L, f(δ_e) is the lift as a function of elevation deflection and is, in general, a nonlinear function. This term is derived for the most part from wind tunnel or flight test data and will cover the complete deflection range.

Lift due to Stabilizer - The L, f(i_T) is the lift as a function of horizontal stabilizer angle. This term is used mostly for trimming those airplanes which have a variable incidence stabilizer.

Provisions are made for changing the incidence setting dictated by flight conditions and airplane controllability. The last term in this equation, F_Z, is the summation of all forces incurred due to the inherent aerial delivery technique or other change in vertical forces such as a gust. This term is similar to that of F_X except that these forces are summed in the vertical (Z) direction. The remaining terms in this equation have been stated in the explanation of Equation (1).

Equation (3)

Equation (3) sums all pitching moments about the airplane center of gravity. This equation is as follows:

$$\Sigma M_{c.g.} = M_{a.c.},\ f(\alpha_{FRL}) + M_{\dot{\theta}}\dot{\theta} + M_{\dot{\alpha}}\dot{\alpha} + M,\ f(\delta_e) + M,\ f(i_T) + M_c$$

$$+ M_{\overline{c.g.}} = I\ddot{\theta}$$

Center of Gravity - The position of the center of gravity has a pronounced effect upon a delivery system. The most forward airplane center of gravity is the most stable aerodynamically, provides the most damping in pitch, is the most critical structurally in terms of tail load and fuselage strength, and requires the most time to extract cargo. This latter situation occurs because the cargo must be loaded more forward to achieve an overall forward center-of-gravity position. The longer the time to extract the more time the airplane has to respond. Accordingly, the most forward center-of-gravity position was used in the Phase II studies.

Airplane Pitching Moment - The term $M_{a.c.},\ f(\alpha_{FRL})$ is the aerodynamic pitching moment about the center of gravity as a function of angle of attack. This term is markedly affected by center-of-gravity shift. When the cargo is extracted and, generally, a large center-of-gravity change occurs, this moment must be mathematically adjusted. Therefore,

$$M_{a.c.},\ f(\alpha_{FRL}) = M_{c.g.},\ f(\alpha_{FRL}) + L,\ f(\alpha_{FRL})\ (\Delta c.g.)$$

where $M_{c.g.},\ f(\alpha_{FRL})$ is the aerodynamic pitching moment at a specified center-of-gravity location before the cargo is extracted and where $\Delta c.g.$ is the difference between the initial center-of-gravity location and the resultant location after cargo extraction.

This term is nonlinear and is always treated as such. Also, the elevator deflection and incidence angle are considered to be zero in this term.

Pitching Moment due to Elevator - The pitching moment due to elevator deflection, M, $f(\delta_e)$, is an important aerodynamic term since its effectiveness can mean the difference between success and failure of a delivery system. This parameter is programmed for both "up and down" deflections and to account for the nonlinear characteristics over the complete range of deflection.

Pitching Moment due to Stabilizer - The pitching moment due to the horizontal stabilizer incidence angle, M, $f(i_T)$, is usually set in the trim position so that essentially zero stick force occurs just prior to drop. Some airplanes have the incidence angle fixed, while others use the angle for trimming. The airplane damping in pitch is represented by the $M_{\dot{\theta}}$ and $M_{\dot{\alpha}}$ terms. $M_{\dot{\theta}}$ is defined as $\partial M/\partial \dot{\theta}$, the rate of change of pitching moment with a rate of change of pitching velocity. This term, along with $M_{\dot{\alpha}}$, is nearly always calculated theoretically because much expense is incurred by any other method, and it has been found that the theoretical method is sufficient. The pitching moment is defined as

$$M = C_m \, q \, S \, \bar{c}$$

where C_m = pitching moment coefficient,

S = airplane wing area, and

$\bar{c}$ mean aerodynamic chord.

differentiating the moment equation with respect to pitching velocity yields

$$\partial M/\partial \dot{\theta} = \partial C_m/\partial \dot{\theta} \, q \, S \, \bar{c}$$

and

$$\partial C_m/\partial \dot{\theta} = -\,2.2\, C_{L_{\alpha_t}} \, S_t/S \;\; \eta_t \left(\ell_T^2/U\bar{c} \right)$$

where

$C_{L_{\alpha_t}}$ = lift curve slope of the horizontal tail

S_t = horizontal-tail area;

S = wing area;

ℓ_T = horizontal-tail length, distance from airplane center of gravity to quarter chord of mean aerodynamic chord of horizontal tail; and

η_t = horizontal-tail efficiency, generally taken as 1.0.

Miscellaneous Pitching Moments - The rate of pitching moment with respect to the rate of change of angle of attack, $M_{\dot{\alpha}}$, is derived in the same manner as $M_{\dot{\theta}}$ except that $\partial C_m / \partial \dot{\alpha}$ is given as follows:

$$\partial C_m / \partial \dot{\alpha} = -2 C_{L_{\alpha_T}} V_H \ell_T / U \; \partial \epsilon / \partial \alpha$$

where

V_H = horizontal-tail volume ratio, and

$\partial \epsilon / \partial \alpha$ = rate of change of downwash with rate of change of angle of attack.

In all aerial delivery systems these terms will be held constant even though they do change slightly with center of gravity. The pitching moment caused by the cargo's sliding aft along the airplane cargo floor, M_c, will vary with extraction rate and cargo weight.

This forcing function must be programmed mathematically so as to adequately describe the pitching moment about the airplane center of gravity caused by the cargo moving in an aft direction.

The term $M_{c.g.}$ is the summation of all pitching moments incurred due to the inherent aerial delivery technique. This moment will vary in most any manner, and the mathematical model must be such that nonlinearities can be programmed.

The moment of inertia as presented in this equation is the summation of the airplane plus that of the cargo. The total pitching moment of inertia is expressed as follows:

$$I = I_a + I_c$$

The moment of inertia of the cargo is referred to the airplane center of gravity by $I_c = mk^2$

where k is the distance from the instantaneous cargo center of gravity to that of the airplane.

The term $\ddot{\theta}$ is the airplane pitching acceleration. This unknown quantity will be computed continually as a time history on the analog computer. The airplane pitching velocity $\dot{\theta}$ will be computed by integrating this acceleration term, i.e. $\dot{\theta} = \int \ddot{\theta}\, dt$

and

$$\theta = \int \dot{\theta}\, dt$$

which is the airplane pitch angle.

LITERATURE AND PATENT SEARCH

A thorough literature and patent search has been made with the aid of the contractor information centers for appropriate and applicable aerial delivery simulation data and devices.

Literature Search

The following information sources were searched:

- International Aerospace Abstracts
- NASA STAR and Confidential STAR
- Defense Documentation Center (DDC)
- Air University Periodical Index
- Defense Logistics Information Exchange
- Index Aeronautics
- Engineering Index
- Key Word in Context (KWIC)

On the basis of the material researched, it appears that only the Princeton Dynamic Model Track is capable of possible adaptation to a simulator for airdrop delivery. The adaptability of this facility is discussed in the section entitled System Conceptual Design. A bibliography and selected abstracts for the literature search are presented on pages 116 and 121, respectively.

Patent Search

A patent search for devices directly related or adaptable to a simulator was made by contractor patent attorneys through appropriate Washington offices. No related patents were revealed on any item applicable to this study.

PHASE II - MATHEMATICAL ANALYSIS AND MODELING

The primary purpose of the Phase II portion of the study was to model and analyze the results of Phase I mathematically. Results derived from the Phase II mathematical analysis were, in turn, parametrically analyzed to determine those which had sufficient criticality of significance to be included in the Phase III conceptual design. Phase II was performed in two steps as follows:

- o Development of mathematical model for analog computer, and
- o Criticality analysis of parameters.

DEVELOPMENT OF MATHEMATICAL MODEL FOR ANALOG COMPUTER

The equations of motion were converted into a mathematical model for determination of the airplane response by means of an analog computer. This portion of the study consisted of the following:

- o Preparation of aerodynamic data
- o Conversion of the equations into scaled wiring diagrams
- o Determination of parameter magnitudes for each computer run
- o Results of computer runs

Aerodynamic Data

In order to establish airplane response characteristics to variations in selected parameters, typical aerodynamic data were necessary. The aerodynamic data for the C-130E airplane were chosen as representative of aerodynamics compatible with airdrop system analysis. The lift, drag, and pitching moment data necessary for this study were derived from C-130 wind tunnel and flight tests. All these aerodynamic data are determined outside of the influence of the ground.

When the flight altitude of an airplane is within a semispan's distance of the ground surface, a change occurs in the three dimensional flow pattern because the local airflow cannot have a vertical component at the ground plane. Thus, the ground plane will furnish a restriction to the flow and alter the wing upwash, downwash, and wing-tip vortices. These changes in aerodynamic characteristics are referred to as "ground effect."

The reduction of the tip or trailing vortices due to the presence of the ground alters the spanwise lift distribution and reduces the induced angle of attack. Therefore, the wing will require a lower angle of attack when in the influence of the ground to produce the same lift

coefficient. The magnitude of the influence varies directly with airplane height above the ground and inversely with the wing span. Inasmuch as the mathematical analysis was a parametric study of airplane response, the use of aerodynamic data outside the influence of the ground was considered to be conservative.

The airplane configuration to which the data apply is as follows: flaps deflected, gear down, ramp door open, and power for level flight. Preliminary calculations were made to determine the amount of elevator deflection required for trim for the stick-fixed computer runs.

In order to investigate the effect of technological development in aerodynamics, the lift, drag, and pitching moment coefficients were varied ± 25 percent relative to their normal limits. This variation is based upon the data shown in Figure 7 which is taken from a Lockheed-Georgia study. The increase in lift is presumed to affect pitching moment to the same degree. Hence, it is considered that the range of parameters used in this study will encompass the values attainable in the 1965-75 time period. These parameters are thus usable in a simulator for that period. The variation in parameters also provides coverage down to the 60-knot speed range.

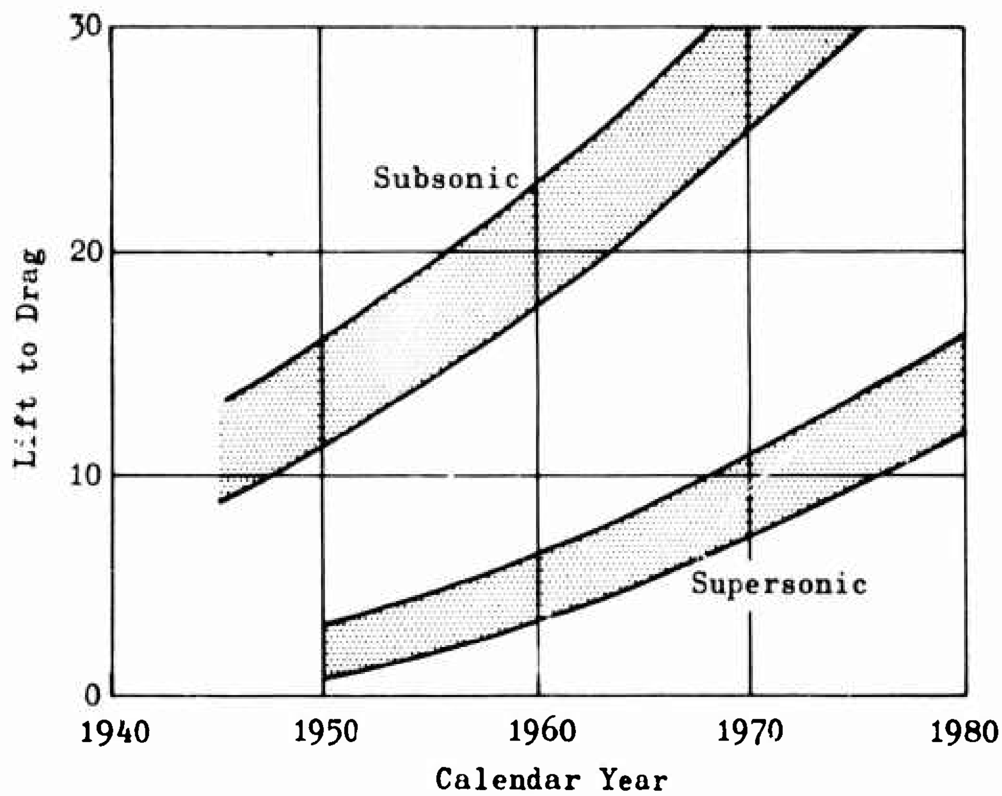


Figure 7 - Predicted Growth of Lift-to-Drag Ratios

It is considered that the aerodynamic data for the C-130 are applicable to other existing airplanes or to those possible in the 1965 to 1975 time period when operating in the subsonic speed range. This is considered to be the case inasmuch as aerodynamic data are normally reduced to coefficient form by mathematically applying dynamic pressure and reference areas or dimensions. Further, inasmuch as all U. S. military airplanes are designed to the same coordinated structural and aerodynamic specifications, certain levels of stability and control must be achieved. The dynamic stability characteristics of all airplanes must meet a specified damping requirement. Accordingly, aerodynamic coefficients between airplanes of a given type vary little and are normally of the same order of magnitude. The C-130 and the CV-2 can be expected to have similar response characteristics because both have the wing located at the top of the fuselage; both have high aspect ratio wings, and both have the same upswept fuselage aft body. A cursory examination of modern U. S. and foreign airplanes which have airdrop capability will reveal similar configurational features. Among these airplanes are the C-130, C-141, C-5A, CV-2, and CV-7. A brief comparison of the C-130 and CV-2 will illustrate the point as follows:

Parameter	C-130E	CV-2
Aspect Ratio	10.1	9.9
Wing Area (square feet)	1745	912
Airfoil Section (root)	64A318	643A4175
Maximum Takeoff Gross Weight (pounds)	175,000	28,000
Maximum Lift Coefficient, flaps down	3.4	3.15
Drag Coefficient @ $C_L = 1.0$	0.066	0.080

Alternatively:

C-130 at GW = 120,000 pounds at 100 knots (Phase II Cond.)

$$C_L = \frac{W}{qs} = \frac{120,000}{33.9(1745)} = 2.03$$

CV-2 at GW = 24,000 pounds at 60 knots

$$C_L = \frac{W}{qs} = \frac{24,000}{12.2(912)} = 2.16$$

It is hence considered that the use of C-130 aerodynamics, plus the variation of these data to higher and lower limits, has achieved applicability of the mathematical analysis to existing and future airplanes with airdrop capability.

Scaled Wiring Diagrams

The equations of motion, written in scaled form, were programmed for solution on a Beckman-Ease analog computer. Existing contractor programs were used without change. Figures 8, 9, 10, and 11 show the symbolic wiring diagrams, along with the equations, scaled equations, and aerodynamic notation. Each wiring diagram describes the scaled equation which is used to derive the magnitudes of the various parameters compatible with the computer capability.

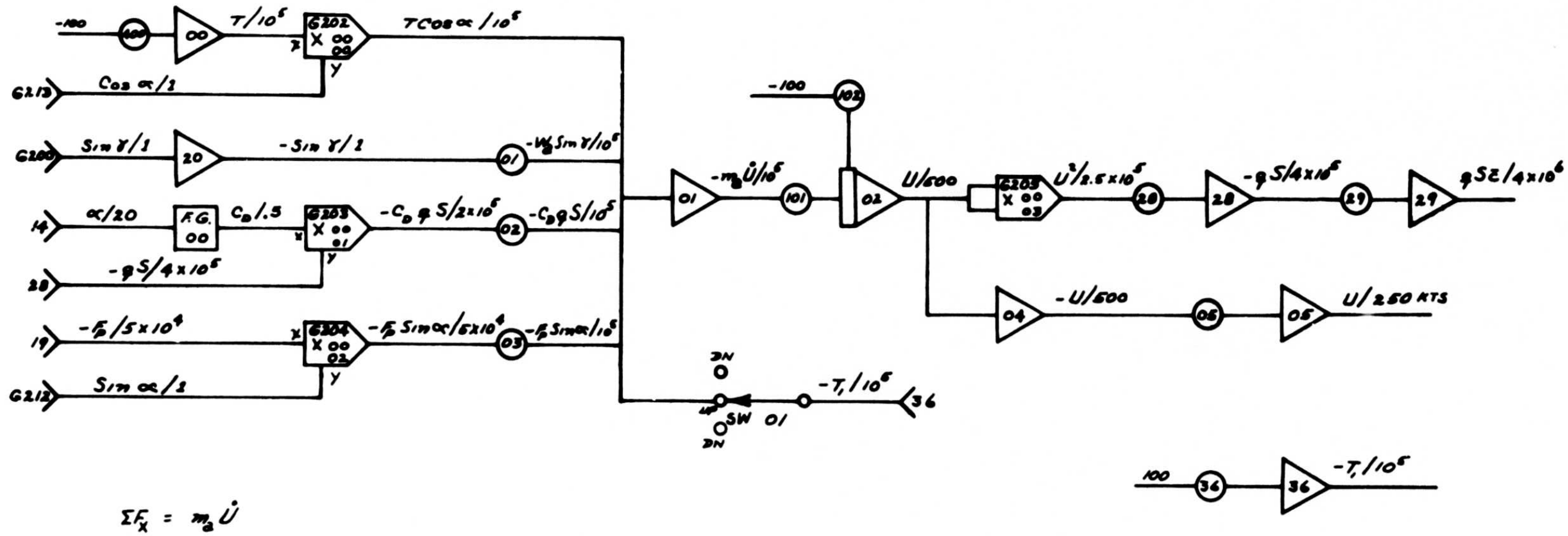
The preparation of the data for analog computation includes calculating the values of lift, drag, and pitching moment coefficients for programming as the function generators for each run. In addition, the servo-set coefficient potentiometer settings, along with input gain settings, were determined for each run.

Computer Run Schedule

Table I presents a computer run schedule and a tabulation of the input data. The candidate parameters are listed along with their magnitudes and range of variation for each run. A summary of these forcing parameters is as follows:

- Thrust
- Airspeed
- Cargo weight
- Flight path angle
- Angle of attack
- Gust effects
- Center of gravity
- Pitching moment due to pitching velocity
- Pitching moment due to angle of attack
- Cable angle
- Lift due to angle of attack
- Lift due to elevator deflection
- Drag
- Tip-off characteristics
- Flap deflection
- Elevator rate
- Pitching moment due to elevator deflection
- Pitching moment due to rate of change of angle of attack
- Cargo extraction acceleration
- Cargo slide distance

The effect of altitude is masked by the computation for true airspeed and for the dynamic pressure which is a basic term in lift, drag, and moment. The effects of mass and moment of inertia are inherent in the analog program and in the lift term.



$\Sigma F_x = m_a\dot{U}$

$m_a\dot{U} = T\cos\alpha - W_a\sin\gamma - C_D q S - F_p\sin\alpha - T_1$

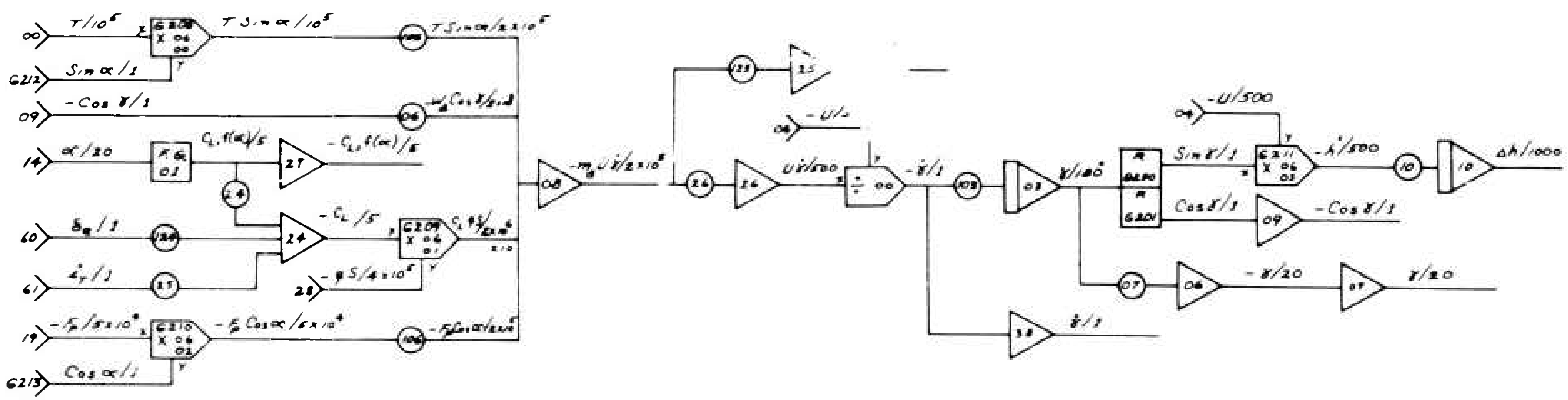
SCALED EQUATION:

$$\frac{m_a\dot{U}}{10^6} = \left[\frac{T}{10^6}\right]\left[\frac{\cos\alpha}{1}\right] - \left[\frac{W_a}{10^6}\right]\left[\frac{\sin\gamma}{1}\right] - \left[\frac{C_D}{.5}\right]\left[\frac{qS}{4\times10^6}\right]\left[2\right] - \left[\frac{F_p}{5\times10^4}\right]\left[\frac{\sin\alpha}{1}\right]\left[\frac{1}{2}\right] - \left[\frac{T_1}{10^6}\right]$$

$$\frac{U}{500} = \int\left[\frac{m_a\dot{U}}{10^6}\right]\left[\frac{200}{m_a}\right] \qquad \frac{U}{250\ KTS} = \left[\frac{U}{500FPS}\right]\left[\frac{1}{1.69}\right]\left[2\right]$$

$$\frac{qS}{4\times10^6} = \left[\frac{U^2}{2.5\times10^5}\right]\left[\frac{\frac{1}{2}\rho S}{1.6}\right] \qquad \frac{qS\bar{c}}{4\times10^6} = \left[\frac{qS}{4\times10^6}\right]\left[\frac{\bar{c}}{10}\right]$$

Figure 8 - Analog Wiring Diagram with Scaled Equations of Aerodynamic Forces Summed in the X Direction



$$\Sigma F_z = -mU\dot{\gamma}$$

$$-m_a U\dot{\gamma} = -T\sin\alpha + W_a\cos\gamma - L_{,}f(\alpha) + L_{,}f(\delta_e) + L_{,}f(i_T) - F_p\cos\alpha$$

SCALED EQUATIONS :

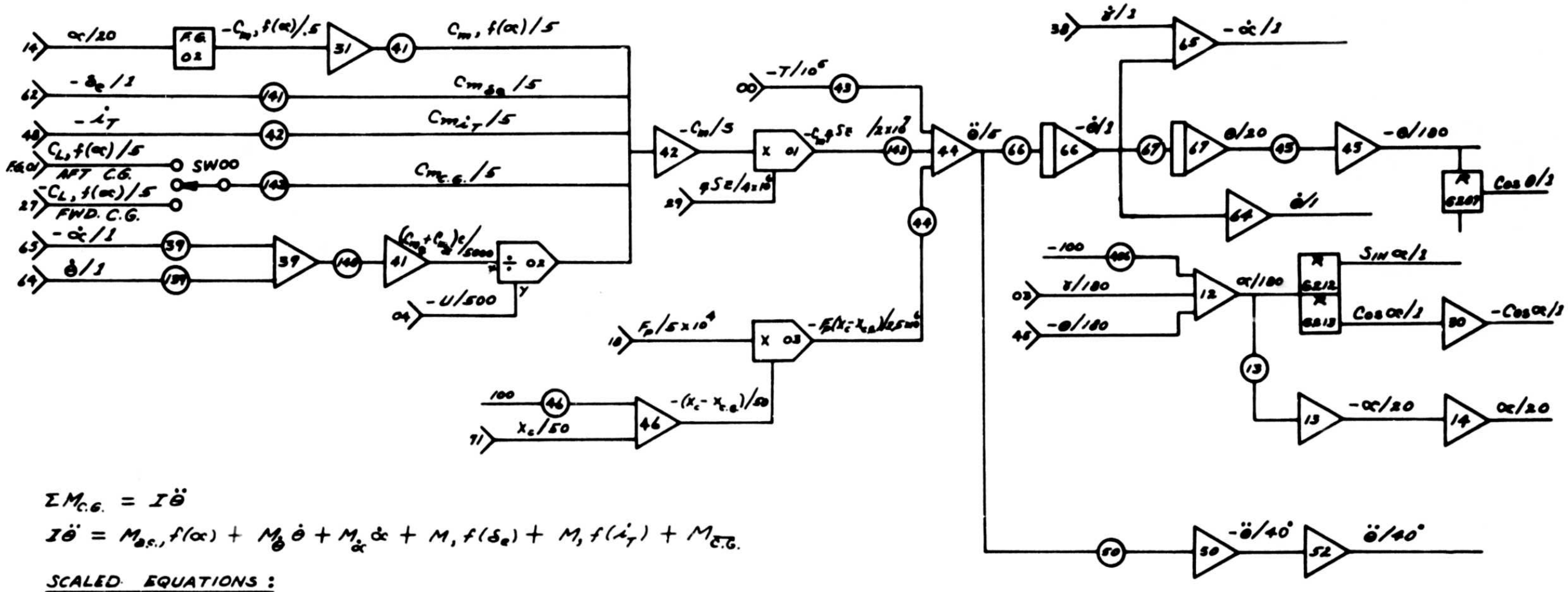
$$\frac{m_a U\dot{\gamma}}{2\times10^5} = \left[\frac{T}{10^6}\right]\left[\frac{\sin\alpha}{1}\right]\left[\frac{1}{2}\right] - \left[\frac{W_a}{2\times10^5}\right]\left[\frac{\cos\gamma}{1}\right] + \left[\frac{C_L qS}{2\times10^6}\right]\left[10\right] - \left[\frac{F_p}{5\times10^4}\right]\left[\frac{\cos\alpha}{1}\right]\left[\frac{1}{4}\right]$$

$$\frac{C_L qS}{2\times10^6} = \left\{\frac{qS}{4\times10^5}\right\}\left\{\left[\frac{C_{L,}f(\alpha)}{5}\right] + \left[\frac{C_{L\delta_e}}{5}\right]\left[\frac{\delta_e}{1}\right] + \left[\frac{C_{Li_T}}{5}\right]\left[\frac{i_T}{1}\right]\right\}$$

$$\frac{\Delta n}{2} = \left[\frac{m_a U\dot{\gamma}}{2\times10^5}\right]\left[\frac{10^5}{W_a}\right] \qquad \frac{U\dot{\gamma}}{500} = \left[\frac{m_a U\dot{\gamma}}{2\times10^5}\right]\left[\frac{400}{m_a}\right]$$

$$\frac{\dot{\gamma}}{1} = \left[\frac{U\dot{\gamma}}{500}\right]\left[\frac{500}{U}\right] \qquad \frac{\dot{\alpha}}{1} = \frac{\dot{\theta}}{1} - \frac{\dot{\gamma}}{1} \qquad \frac{\gamma}{180} = \int\frac{\dot{\gamma}}{57.3}\left[\frac{57.3}{180}\right] \qquad \frac{\dot{h}}{500} = \left[\frac{U}{500}\right]\left[\frac{\sin\gamma}{1}\right] \qquad \frac{h}{1000} = -\int\frac{\dot{h}}{500}\left[\frac{1}{2}\right]$$

Figure 9 - Analog Wiring Diagram with Scaled Equations of Aerodynamic Forces Summed in the Z Direction



$$\Sigma M_{C.G.} = I\ddot{\theta}$$

$$I\ddot{\theta} = M_{\delta s.,} f(\alpha) + M_{\dot{\theta}}\dot{\theta} + M_{\dot{\alpha}}\dot{\alpha} + M, f(\delta_e) + M, f(i_T) + M_{\overline{C.G.}}$$

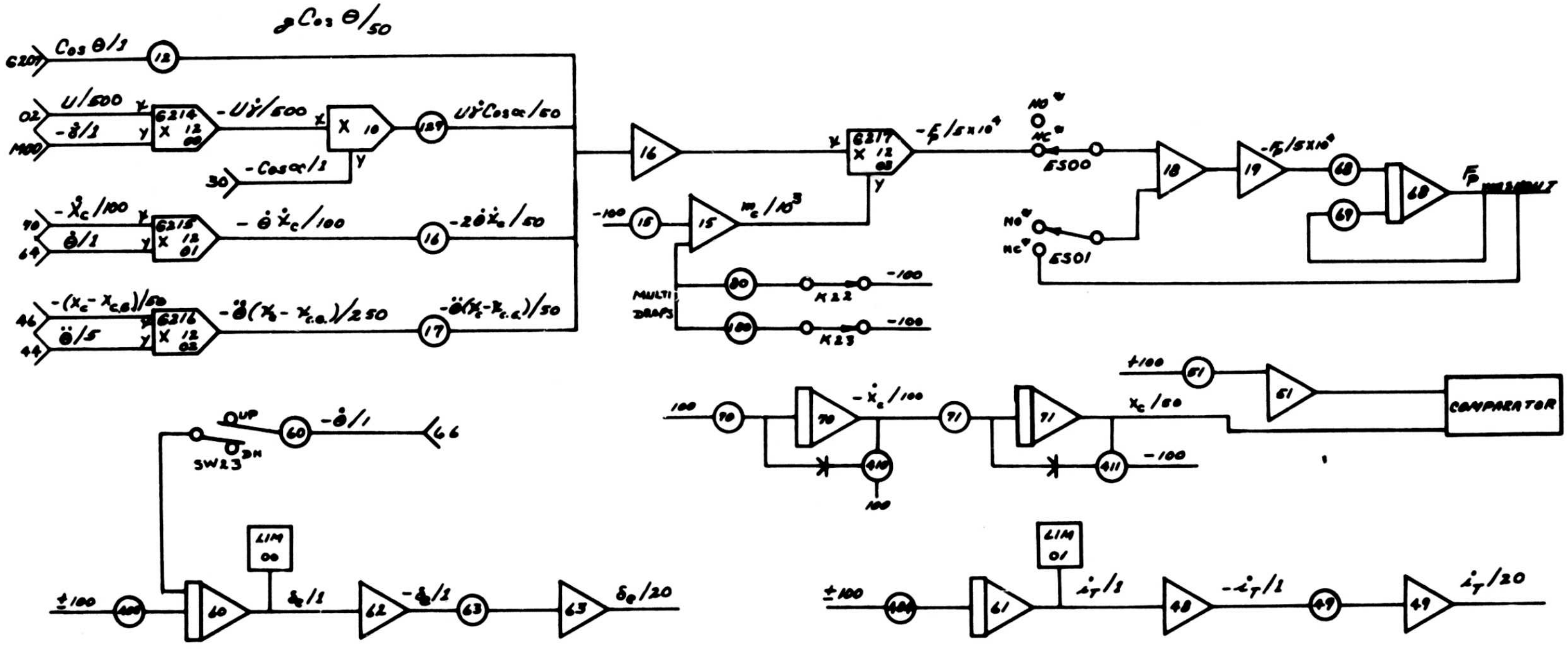
SCALED EQUATIONS :

$$\frac{\ddot{\theta}}{5} = \left[\frac{T}{10^8}\right]\left[\frac{2\times10^4\, l_e}{I_y}\right] + \left[\frac{C_m q S \bar{c}}{2\times10^7}\right]\left[\frac{4\times10^6}{I_y}\right] + \left[\frac{F_P}{5\times10^4}\right]\left[\frac{x_c - x_{c.g.}}{50}\right]\left[\frac{5\times10^8}{I_y}\right]$$

$$\frac{C_m q S \bar{c}}{2\times10^7} = \left\{\frac{q S \bar{c}}{4\times10^6}\right\}\left\{\frac{C_{m_1} f(\alpha)}{5} + \frac{C_{m_{\delta e}}}{5}\,\frac{\delta_e}{1} + \frac{C_{m_{i_T}}}{5}\,\frac{i_T}{1} \pm \frac{C_L, f(\alpha)}{5}\,\frac{\bar{x}}{\bar{c}} + \left[\frac{\bar{c}}{(2)(25)}\,\frac{500}{U}\right]\left[\frac{C_{m_{\dot{\alpha}}}}{100}\,\frac{\dot{\alpha}}{1} + \frac{C_{m_{\dot{\theta}}}}{100}\,\frac{\dot{\theta}}{1}\right]\right\}$$

$$\frac{\dot{\theta}}{1} = \int \frac{\ddot{\theta}}{5}\,\frac{5}{1} \qquad \frac{\alpha}{180} = \frac{\theta}{180} - \frac{\gamma}{180} \qquad \frac{\alpha}{20} = \frac{\alpha}{180}\,\frac{9}{1}$$

Figure 10 – Analog Wiring Diagram with Scaled Equations of Aerodynamic Moments Summed about the Airplane Center of Gravity



$$F_p = W_c \cos\theta + m_c U\dot\gamma\cos\alpha - m_c\dot\theta\dot x_c - m_c(x_c - x_{c.g.})\ddot\theta$$

SCALED EQUATIONS:

$$\frac{F_p}{5\times10^4} = \left\{\frac{m_c}{10^3}\right\}\left\{\left[\frac{g}{50}\right]\left[\frac{\cos\theta}{1}\right] + \left[\frac{U}{500}\right]\left[\frac{\dot\gamma}{1}\right]\left[\cos\alpha\right]\left[10\right] - \left[2\right]\left[\frac{\dot\theta}{1}\right]\left[\frac{\dot x}{100}\right]\left[2\right] - \left[\frac{x_c - x_{c.g.}}{50}\right]\left[\frac{\ddot\theta}{5}\right]\left[5\right]\right\}$$

$$\frac{\dot x_c}{100} = \int \frac{\ddot x_c}{100} \qquad \frac{x_c}{50} = \int \frac{\dot x_c}{100}\, 2$$

* NO NORMALLY OPEN

* NC NORMALLY CLOSED

Figure 11 - Analog Wiring Diagram with Scaled Equations of Platform Force, F_p

TABLE I

ANALOG COMPUTER RUN SCHEDULE

Parameters	Run No. 1*	Run No. 2	Run No. 3	Run No. 4**	Run No. 5	Run No. 6	Run No. 7
True Airspeed, knots	140	-	-	-	100	180	220
Cargo Weight, pounds	3,000	10,000	15,000	-	-	-	-
C.G., Percent $\bar{c}$	19	-	-	-	-	-	-
Cargo Acceleration, g's	1	-	-		-	-	-
Cable Angle, degrees	0	-	-	-	-	-	-
Cargo Slide Distance, feet	42.8	-	-	-	-	-	-
Tip-Off Type	Half	-	-	-	-	-	-
Flap Deflection, degrees	23.7	24.4	24.9	25.5	18.0	11.6	5.0
T_c	0.17	0.26	0.31	0.365	0.70	0.22	0.166
D vs α	D$\sim$	-	-	-	-	-	-
L vs α	L$\sim \alpha$	-	-	-	-	-	-
M vs α	M vs α	-	-	-	-	-	-
M vs $\dot{\theta}$	M vs $\dot{\theta}$	-	-	-	-	-	-
M vs $\dot{\alpha}$	M vs $\dot{\alpha}$	-	-	-	-	-	-
M vs δ_e	M vs δ_e	-	-	-	-	-	-
L vs δ_e	L$\sim \delta_e$	-	-	-	-	-	-
Gust	-	-	-	-	-	-	-

*All runs stick fixed unless necessary to apply elevator to avoid exceeding limit load factor.

**Run No. 4 being used to illustrate force-down ejection.

ERRATUM

TO

USAAVLABS TECHNICAL REPORT 66-19

On page 36, make the following changes:

Third line: Delete two asterisks after "Run No. 4".

Last line: Delete footnote.

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TABLE I (continued)

Parameters	Run No. 8	Run No. 9	Run No. 10	Run No. 11	Run No. 12	Run No. 13	Run No. 14
True Airspeed, knots	140	-	-	-	-	-	140
Cargo Weight, pounds	-	-	-	-	-	-	20,000
C.G., Percent $\bar{c}$	22	26	29	19	-	-	19
Cargo Acceleration, g's	-	-	-	-	-	-	-
Cable Angle, degrees	-	-	-	-10	10	15	0
Cargo Slide Distance, feet	42.1	41.5	40.6	42.8	-	-	30
Tip-Off Type	-	-	-	-	-	-	Half
Flap Deflection, degrees	25.5	25.5	25.5	25.5	-	25.5	25.5
T_c	0.365	0.365	0.365	0.365	-	0.365	0.365
D vs α	-	-	-	-	-	-	-
L vs α	-	-	-	-	-	-	-
M vs α	-	-	-	-	-	-	-
M vs $\dot{\theta}$	-	-	-	-	-	-	-
M vs $\dot{\alpha}$	-	-	-	-	-	-	-
M vs δ_e	-	-	-	-	-	-	-
L vs δ_e	-	-	-	-	-	-	-
Gust	-	-	-	-	-	-	-

TABLE I (continued)

Parameters	Run No. 15	Run No. 16	Run No. 17	Run No. 18	Run No. 19	Run No. 20	Run No. 21
True Airspeed, knots	-	-	-	-	-	-	-
Cargo Weight, pounds	-	-	-	-	-	-	-
C.G., Percent $\bar{c}$	-	-	-	-	-	-	-
Cargo Acceleration, g's	-	-	-	-	-	-	-
Cable Angle, degrees	-	-	-	-	-	-	-
Cargo Slide Distance, feet	20	10	42.8	-	-	-	-
Tip-Off Type	-	-	Step	Whole	1.5 Whl	Half	-
Flap Deflection, degrees	25.5	25.5	25.5	25.5	25.5	25.5	25.5
T_c	0.365	0.365	0.365	0.365	0.365	0.365	0.365
D vs α						1/	2/
L vs α	-	-	-	-	-	-	-
M vs α	-	-	-	-	-	-	-
M vs $\dot{\theta}$	-	-	-	-	-	-	-
M vs $\dot{\alpha}$	-	-	-	-	-	-	-
M vs δ_e	-	-	-	-	-	-	-
L vs δ_e	-	-	-	-	-	-	-
Gust	-	-	-	-	-	-	-

1/ D vs α curve to be decreased 25 percent in D

2/ D vs α curve to be increased 25 percent in D

TABLE I (continued)

Parameters	Run No. 22	Run No. 23	Run No. 24	Run No. 25	Run No. 26	Run No. 27	Run No. 28
True Airspeed, knots	-	-	Near Stall			140	
Cargo Weight, pounds	-	-	-	-	-	20,000	-
C.G., Percent $\bar{c}$	-	-	-	-	-	19	-
Cargo Acceleration, g's	-	-	-	-	-	1	-
Cable Angle, degrees	-	-	-	-	-	0	-
Cargo Slide Distance, feet	-	-	-	-	-	42.8	-
Tip-Off Type	-	-	-	25.5	25.5	Half	-
Flap Deflection, degrees	25.5	25.5	25.5	0.365	0.365	25.5	25.5
T_c	0.365	0.365	0.365	-	-	0.365	0.365
D vs α	D vs α	-	-	-	-	-	-
L vs α	3/	4/	4/	-	-	-	-
M vs α	-	-	-	-	-	-	-
M vs $\dot{\theta}$	-	-	-	5/	6/	M vs α	-
M vs $\dot{\alpha}$	-	-	-	-	-	0.5 $M_{\dot{\theta}}$	1.5 $M_{\dot{\theta}}$
M vs δ_e	-	-	-	-	-	-	-
L vs δ_e	-	-	-	-	-	-	-
Gust	-	-	-	-	-	-	-

3/ L vs α curve to be decreased 25 percent in L
4/ L vs α curve to be increased 25 percent in L
5/ M vs α curve to be decreased 25 percent in M
6/ M vs α curve to be increased 25 percent in M

TABLE I (continued)

Parameters	Run No. 29	Run No. 30	Run No. 31	Run No. 32	Run No 33	Run No. 34	Run No. 35
True Airspeed, knots	-	-	-	-	-	-	-
Cargo Weight, pounds	-	-	-	-	-	-	-
C. G., Percent $\bar{c}$	-	-	-	-	-	-	-
Cargo Acceleration, g's	-	-	-	-	0.5	1.5	2.0
Cable Angle, degrees	-	-	-	-	-	-	-
Cargo Slide Distance, feet	-	-	-	-	-	-	-
Tip-Off Type	-	-	-	-	-	-	-
Flap Deflection, degrees	25.5	-	25.5	25.5	28.6	23.0	21.9
T_c	0.365	-	0.365	0.365	0.27	0.46	0.56
D vs α	-	-	-	-	-	-	-
L vs α	-	-	-	-	-	-	-
M vs α	-	-	-	-	-	-	-
M vs $\dot{\theta}$	-	-	-	-	-	-	-
M vs $\dot{\alpha}$	2.0 $M_{\dot{\theta}}$	$M_{\dot{\theta}}$	-	-	-	-	-
M vs δ_e	-	0.5 M	1.5 $M_{\dot{\alpha}}$	2.0 $M_{\dot{\alpha}}$	$M_{\dot{\alpha}}$	-	-
L vs δ_e	-	-	-	-	-	-	-
Gust	-	-	-	-	-	-	-

TABLE I (continued)

Parameters	Run No. 36	Run No. 37	Run No. 38	Run No. 39	Run No. 40	Run No. 41	Run No. 42
True Airspeed, knots	–	–	–	–	140	–	–
Cargo Weight, pounds	–	–	–	–	20,000	–	–
C.G., Percent $\bar{c}$	–	–	–	–	19	–	–
Cargo Acceleration, g's	1.0	–	–	–	1	–	–
Cable Angle, degrees	–	–	–	–	0	–	–
Cargo Slide Distance, feet	–	–	–	–	42.8	–	–
Tip-Off Type	–	–	–	–	Half	–	–
Flap Deflection, degrees	25.5	25.5	25.5	25.5	25.5	25.5	25.5
τ_c	0.365	0.365	0.365	0.365	0.365	0.365	0.365
D vs α	–	–	–	–	D $\sim \alpha$	–	–
L vs α	–	–	–	–	L $\sim \alpha$	–	–
M vs α	–	–	–	–	M $\sim \alpha$	–	–
M vs $\dot{\theta}$	–	–	–	–	M $\sim \theta$	–	–
M vs $\dot{\alpha}$	–	–	–	–	M $\sim \dot{\alpha}$	–	–
M vs δ_e	–	–	–	–	M $\sim \delta_e$	–	–
L vs δ_e	–	–	–	–	L $\sim \delta_e$	–	–
Gust	d_1	d_2	d_3	d_4	–	–	–

Note: Elev. Rate, Deg/Sec – gain = 1 gain = 2 gain = 3 gain = 4 gain = 5 gain = 10

d_1 = 85.6 ft.
d_2 = 171.25 ft.
d_3 = 256.87 ft.
d_4 = 356.87 ft.

TABLE I (continued)

Parameters	Run No. 43	Run No. 44	Run No. 45	Run No. 46 *
True Airspeed, knots	-	-	-	-
Cargo Weight, pounds	-	-	-	-
C.G., Percent $\bar{c}$	-	-	-	-
Cargo Acceleration, g's	-	-	-	-
Cable Angle, degrees	-	-	-	-
Cargo Slide Distance, feet	-	-	-	-
Tip-Off Type	-	-	-	-
Flap Deflection, degrees	25.5	-	-	-
T_c	0.365	-	-	-
D vs α	-	-	-	Data from Run No. 4
L vs α	-	-	-	
M vs α	-	-	-	
M vs $\dot{\theta}$	-	-	-	
M vs $\dot{\alpha}$	-	-	-	
M vs δ_e	-	-	-	
L vs δ_e	-	-	-	
Gust	-	-	-	

* Run No. 46 being used to illustrate force-down ejection.

The basic procedure for preparing input data consisted of selecting nominal, or reference, values for each of the parameters. From these initial reference values, runs were made varying the parameters, one at a time, while all others remained constant at reference value. Run 4, shown by Table I, is a standard or reference value for this series of computer runs, and thus provides the fourth variation in magnitude for the forcing parameter.

Cargo weight was varied in Runs 1 through 4; four values were used to cover the complete range of from 3000 to 20,000 pounds. The airspeed was increased in Runs 5 through 7 by 40-knot increments between 100 to 220 knots while carrying the 20,000-pound cargo. There were four variations of airplane center of gravity, Runs 8 through 10, beginning with the most forward and proceeding to the most rearward. The variation of cable angles, Runs 11 through 13, includes the values expected under actual extractions and ranged from -10 to +15 degrees. The cargo sliding distance relative to the cargo floor was varied in Runs 14 through 16. Including Run 4, the position varied between the most forward position of the cargo center of gravity and the most aft position for a 20,000-pound cargo weight. The tip-off phenomenon was investigated by extensions of the cargo ramp door lip in Runs 17 to 19.

The lift, drag, and pitching moment versus angle of attack data were programmed for input corresponding to the specific flight condition for a given run.

Runs 20 and 21 provided for an increase and decrease of the drag by 25 percent, while Runs 22 and 23 similarly varied lift, with a stall lift investigation on Run 24. Runs 25 and 26 investigated the effect of ± 25 percent variation in moment. Pitch damping was checked in Runs 27 to 29 and was followed by angle-of-attack damping in Runs 30 to 33.

The very significant effect of cargo extraction acceleration was programmed for Runs 33 through 35 with a total variation, including Run 4, from 0.5 g to 2.0 g.

Runs 36 through 39 program the effect of dropping cargo while entering a gust. The run schedule shows the cargo to be dropped at successive distances into the gust (a 1 - cos shape build-up in gust velocity is assumed).

The suggested runs were performed with stick fixed, that is without corrective elevator deflection. Each computer run was then monitored visually as the data were reproduced by the analog recorder. On those runs wherein the limit load factor of 3.0 was exceeded, additional runs were made; the corrective elevator was used to reduce the load factor to acceptable values. For the aft gravity extractions, the elevator was gradually deflected until a sufficient nose-up attitude was

attained to permit the cargo to slide out because of its own weight. The downward-forced ejections were performed by abruptly decreasing the airplane weight with a step function.

Runs 40 through 45 were included to investigate the effect of increasing the rate of elevator deflection. Finally, Run 46 was the downward-forced ejection which utilized data from Run 4 with a step function reduction in cargo weight.

Computer Results

Computer results are shown in Figures 12 through 25 and are presented in the form of time history displays where the effect of a given quantity is revealed as it was investigated over a significant range while all other parameters were held constant. Throughout the analysis, 15 parameters were recorded with each analog run. Sixteen recording channels were available but the elevator trace was duplicated to provide a common trace on each record series. (The recording of these 15 quantities, although not entirely necessary to show airplane response, does provide a measure of credence to the accuracy of the output data.)

Past experience in analysis and flight testing of cargo airplanes has shown that application of corrective elevator extends the usefulness of the airplane by increasing the droppable weight. This results from the tendency of the airplane to exceed limit load factor without application of elevator as the drop weight increases. (Limit load factor for structural specifications, defined as the load factor which establishes a strength level for design of the airplane and components and is the maximum load factor normally authorized for operations.) However, in the interests of complete analysis, the airplane responses for this study were determined with and without corrective elevator as shown by Figures 12 and 13. The elevator deflection was made an input by wiring a simple autopilot into the analog which was sensitive to pitching velocity.

The time history data are presented to show the effects of each parameter under investigation and, with the exception of Figure 12, are presented with elevator deflection only in the interests of conciseness. The data are arranged on each figure to show the airplane response as that parameter is increased when the figure is viewed from left to right. The time scale on each figure is 1.0 second for every two heavy lines. A time mark, time zero, indicates the beginning of each elevator trace.

All time histories in this document are produced by an Offner eight-channel oscillograph recorder which is operated directly from the analog computer command. The records, which have been photographed, retain the accurate details of the traces.

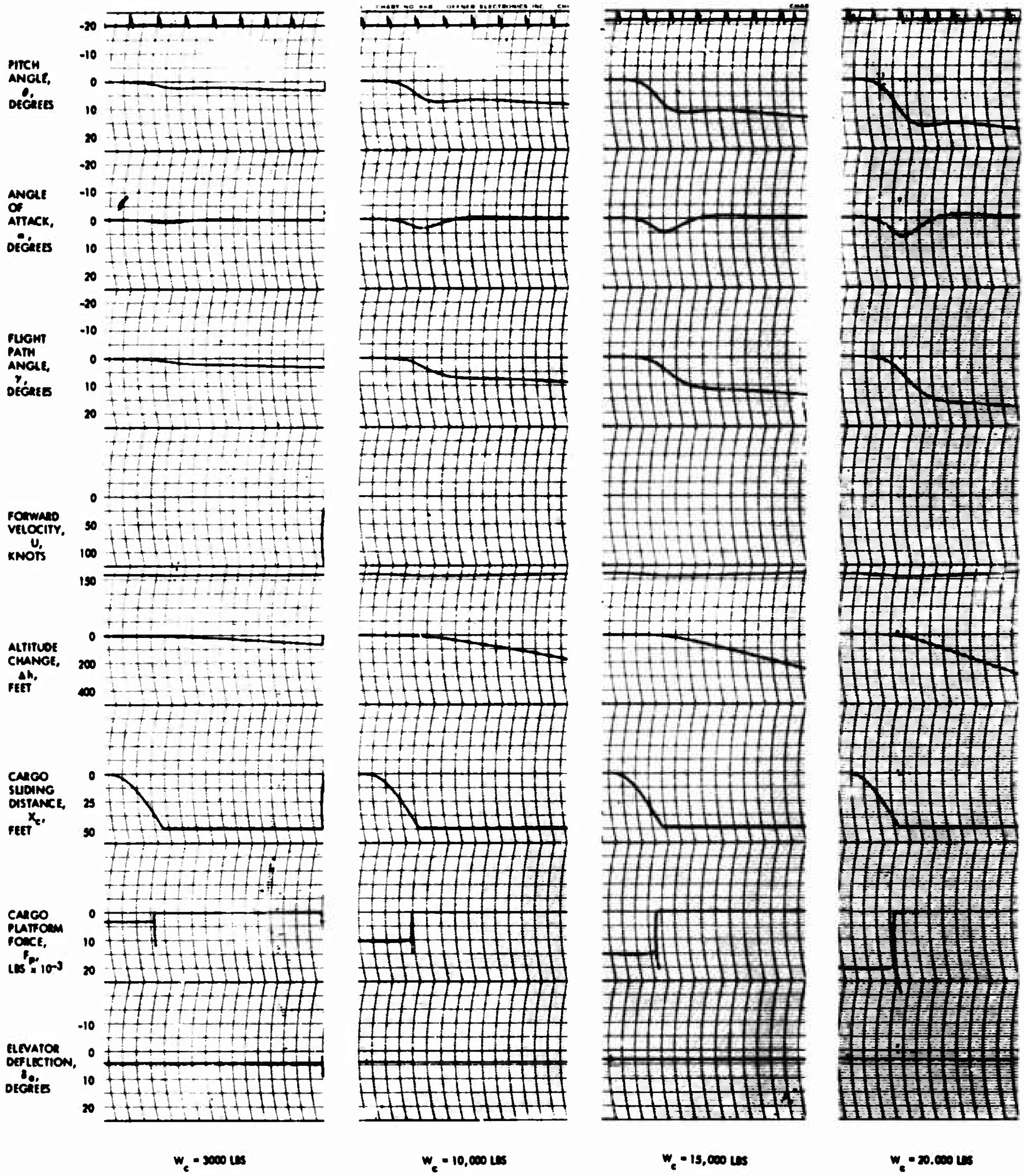


Figure 12A - Time Histories Showing the Effect of Increasing Cargo Weight, No Elevator Deflection

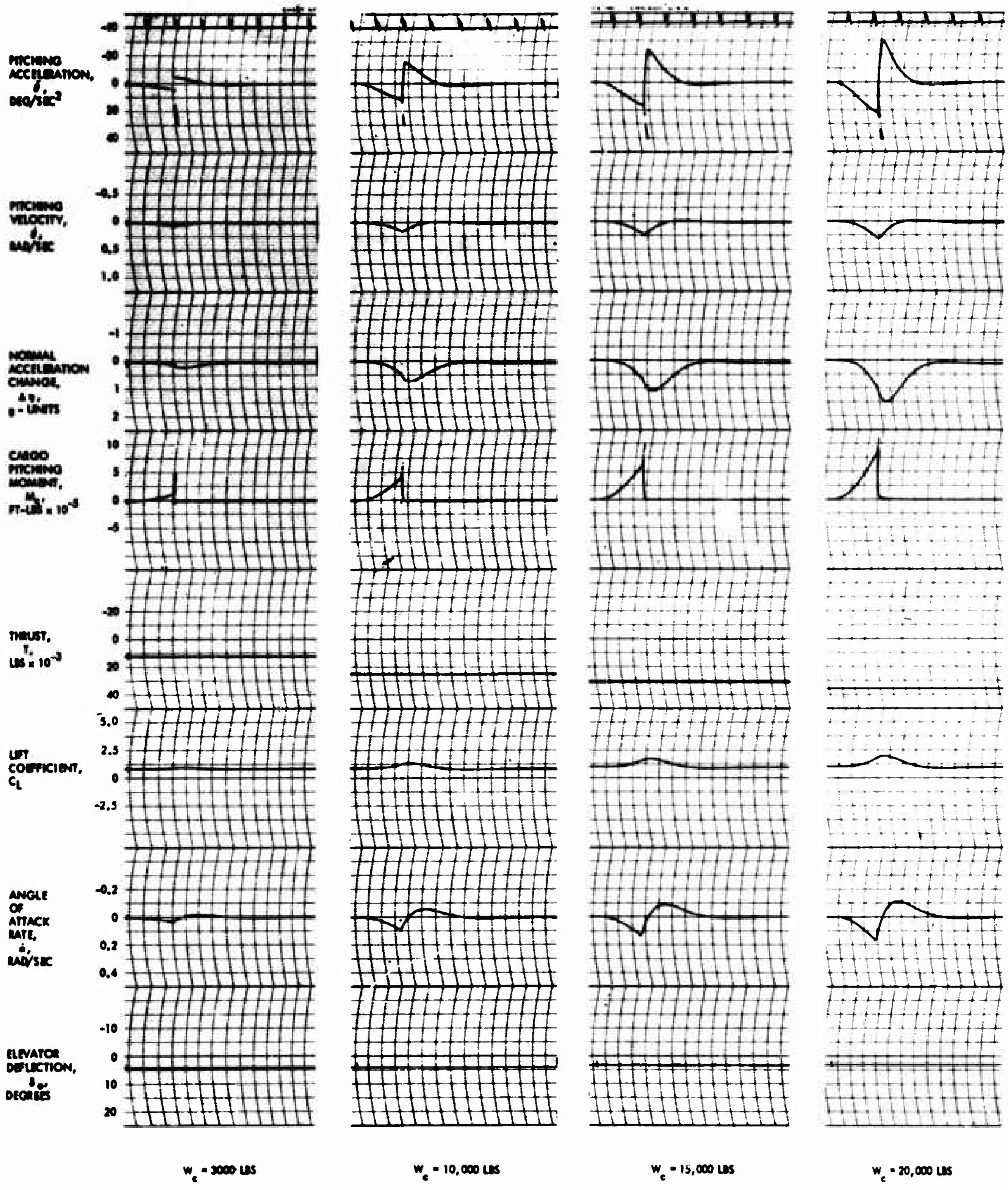


Figure 12B - Time Histories Showing the Effect of Increasing Cargo Weight, No Elevator Deflection

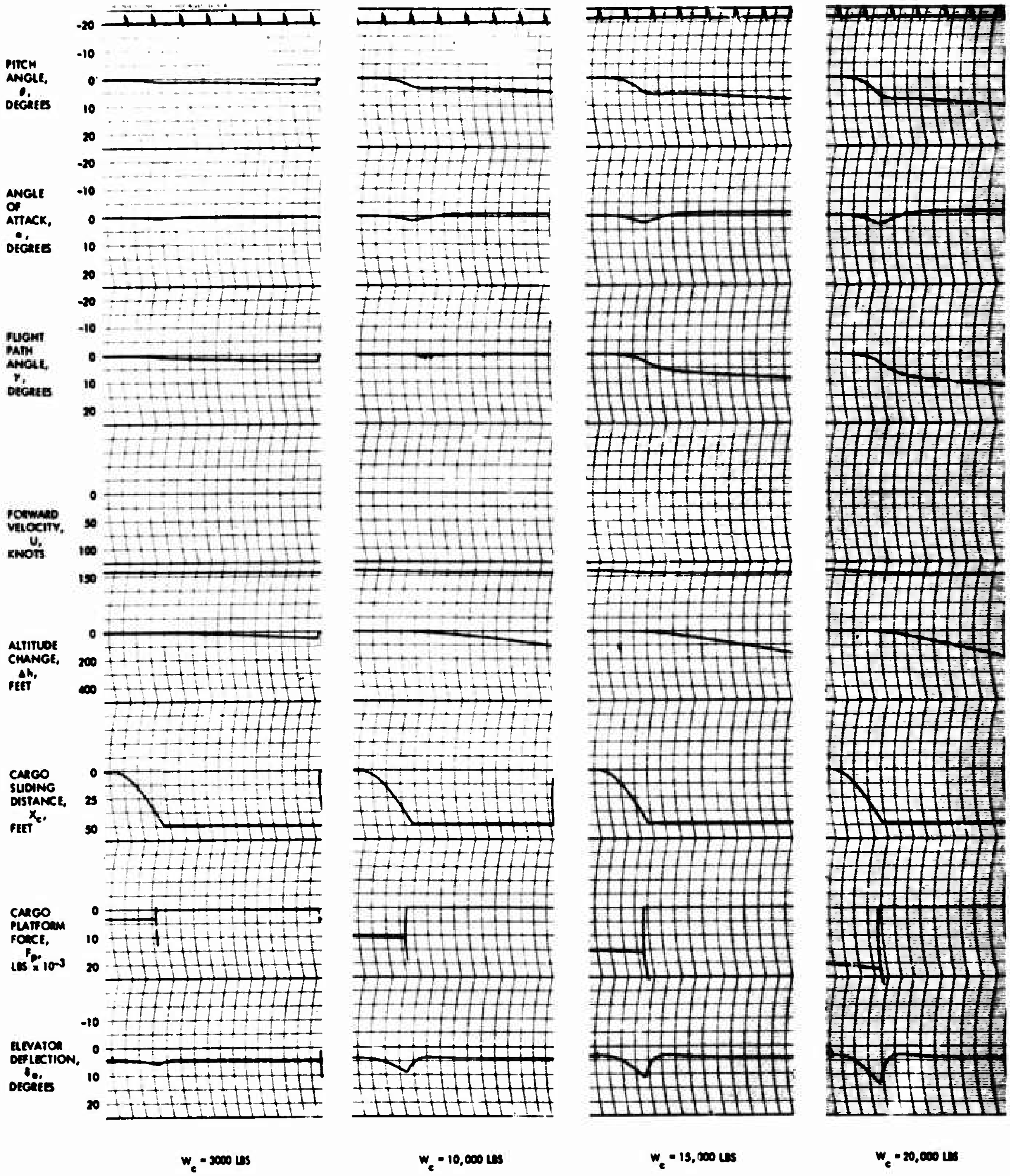


Figure 13A - Time Histories Showing the Effect of Increasing Cargo Weight, with Elevator Deflection

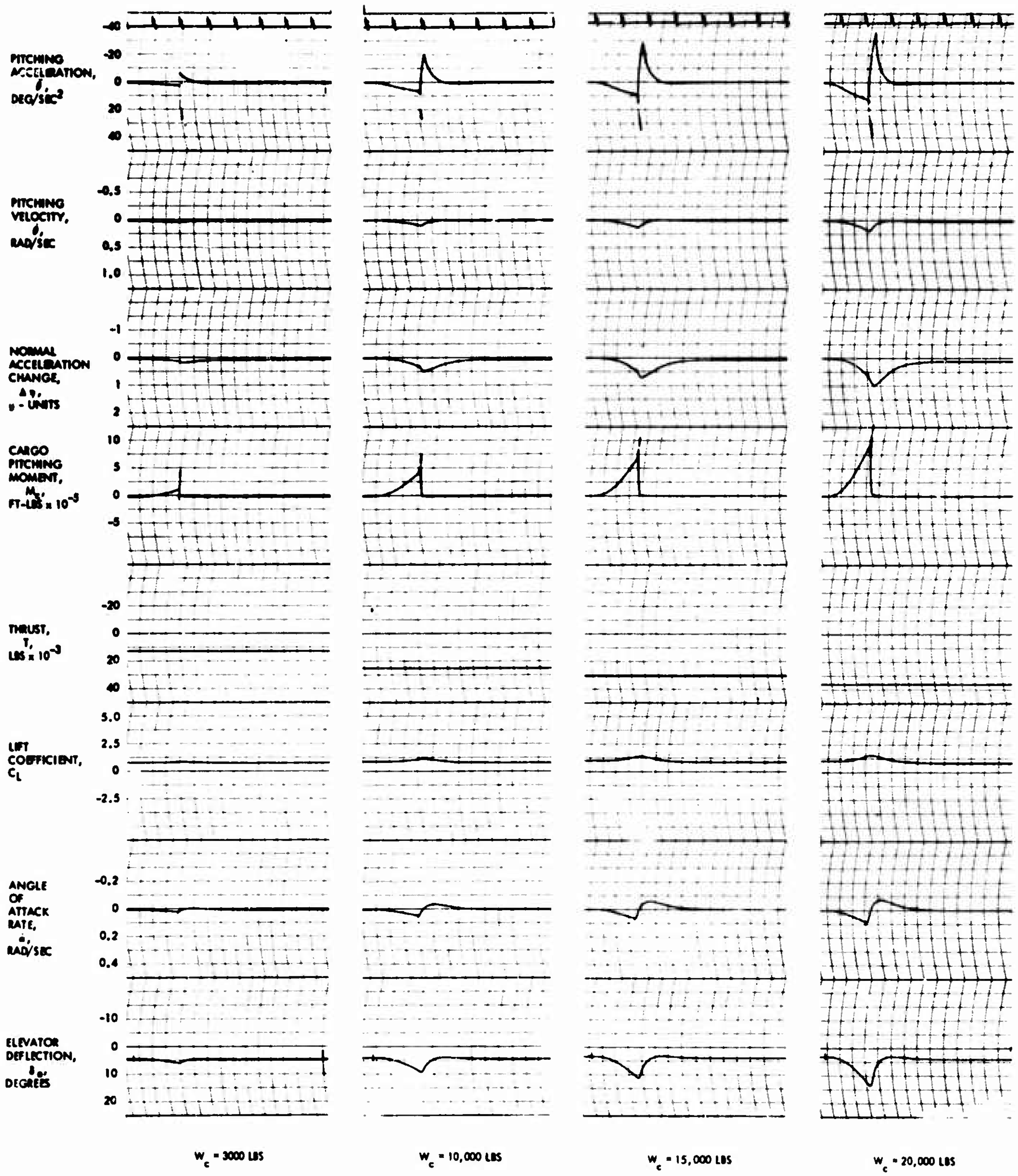


Figure 13B - Time Histories Showing the Effect of Increasing Cargo Weight, with Elevator Deflection

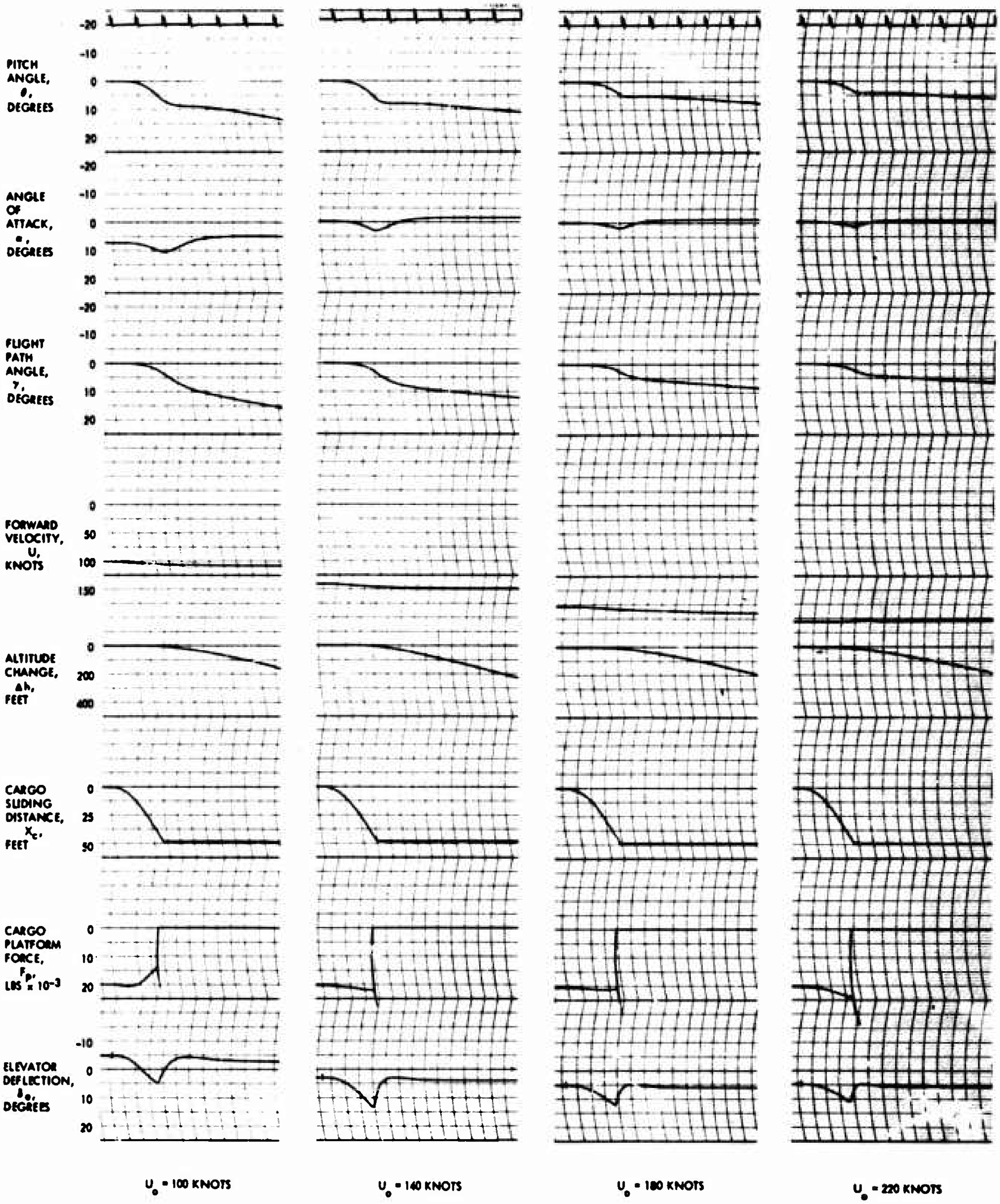


Figure 14A - Time Histories Showing the Effect of Increasing Initial Forward Velocities, with Elevator Deflection

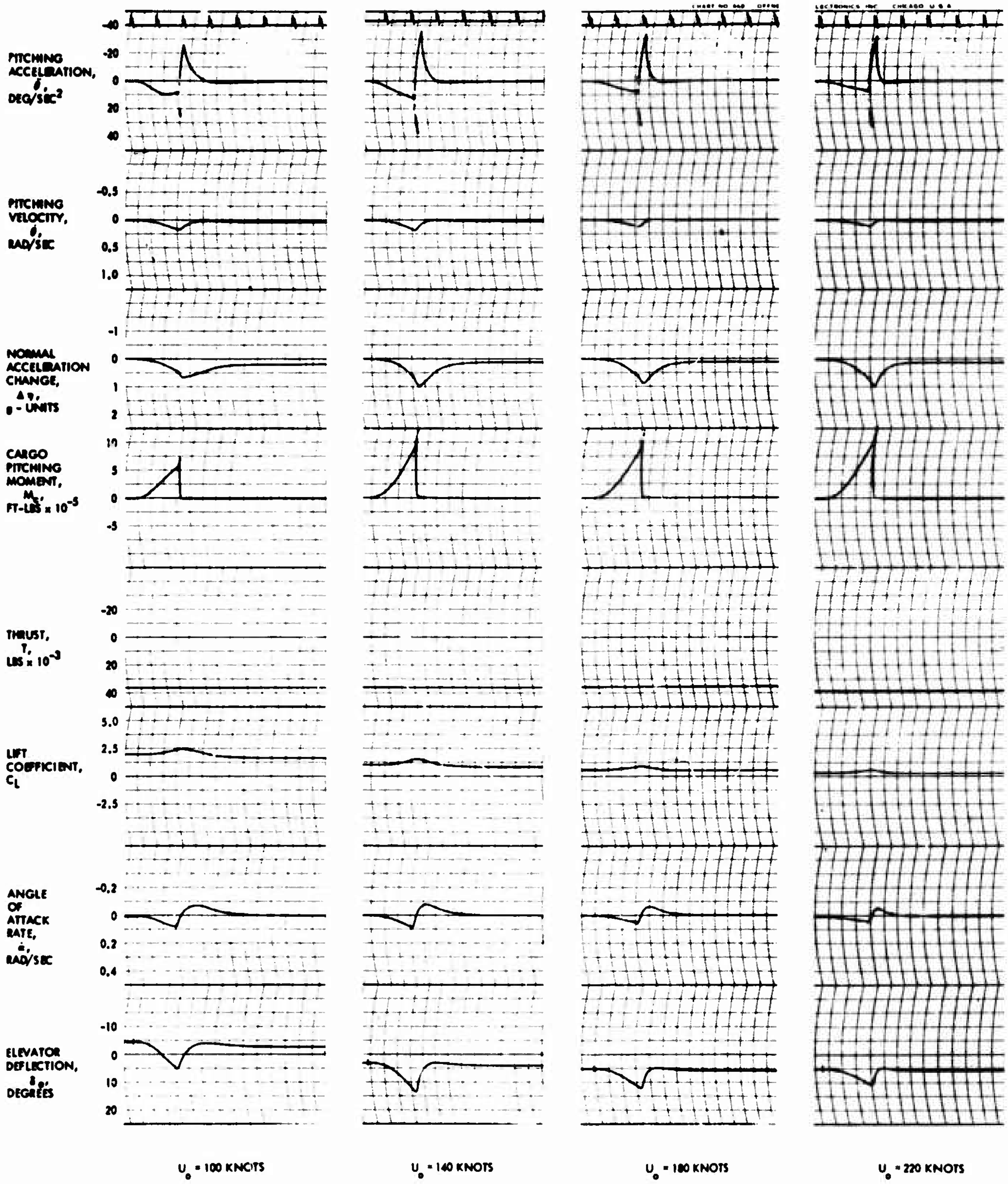


Figure 14B - Time Histories Showing the Effect of Increasing Initial Forward Velocities, with Elevator Deflection

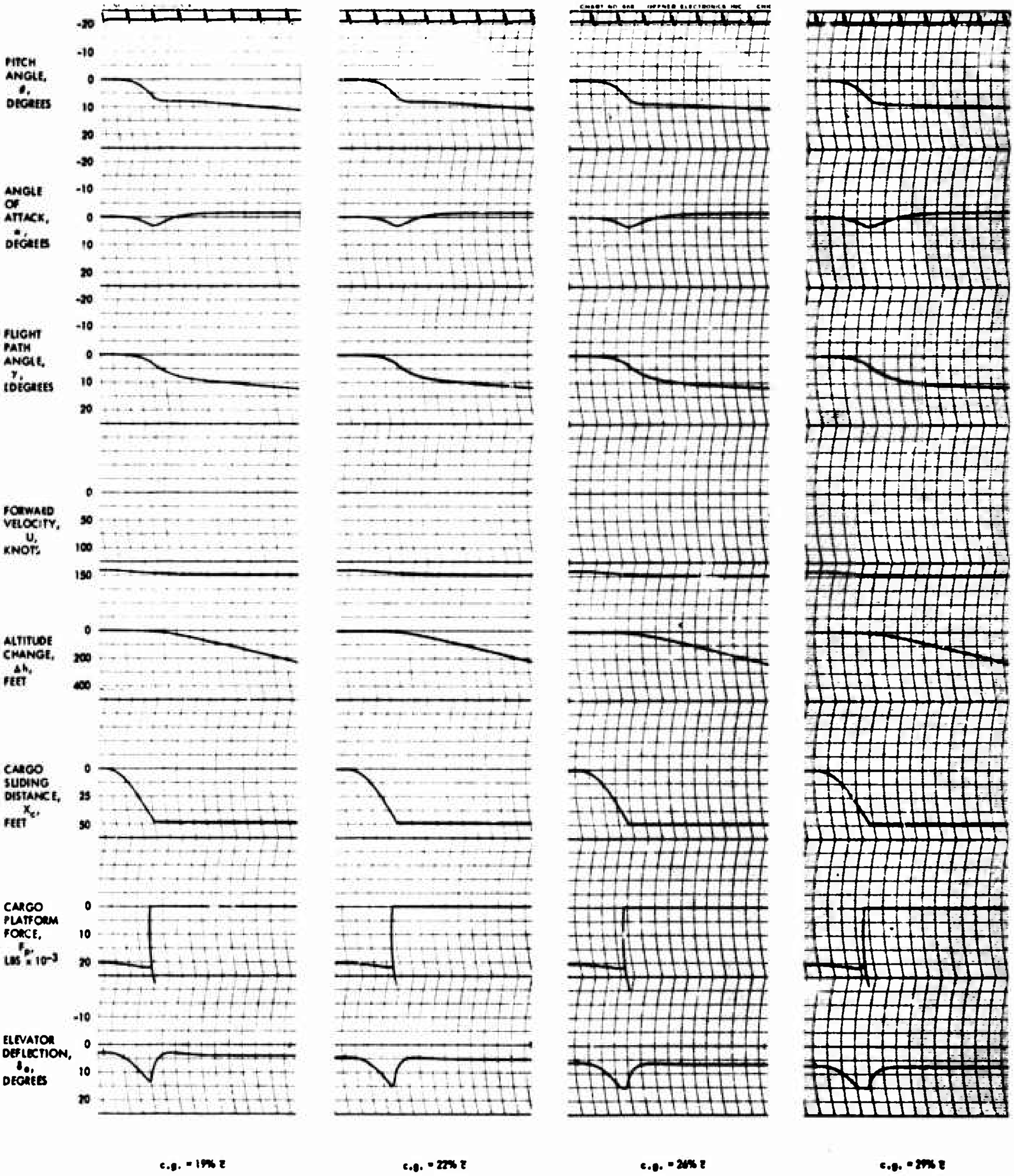


Figure 15A - Time Histories Showing the Effect of Increasing Airplane Center-of-Gravity Location, with Elevator Deflection

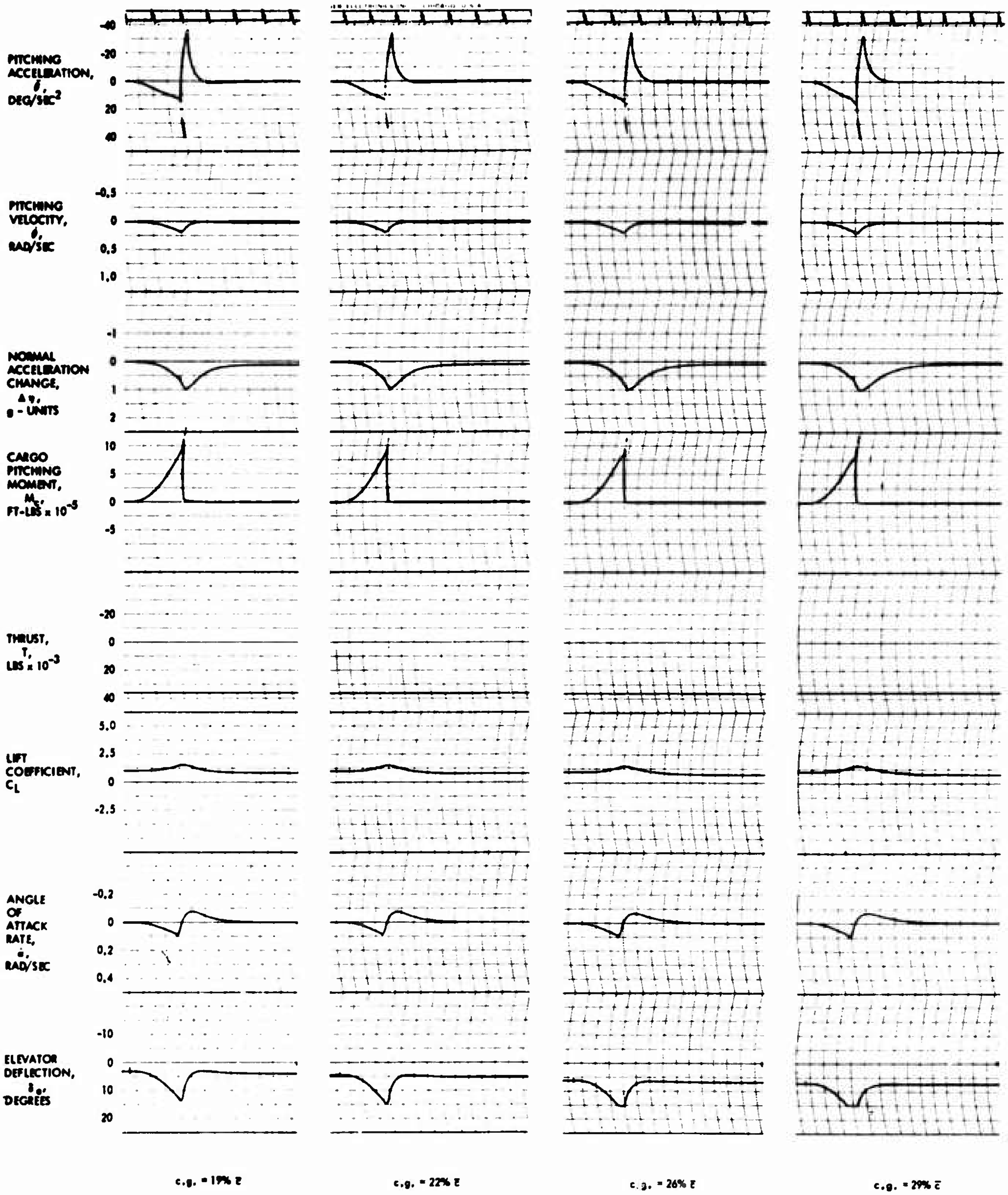


Figure 15B - Time Histories Showing the Effect of Increasing Airplane Center-of-Gravity Location, with Elevator Deflection

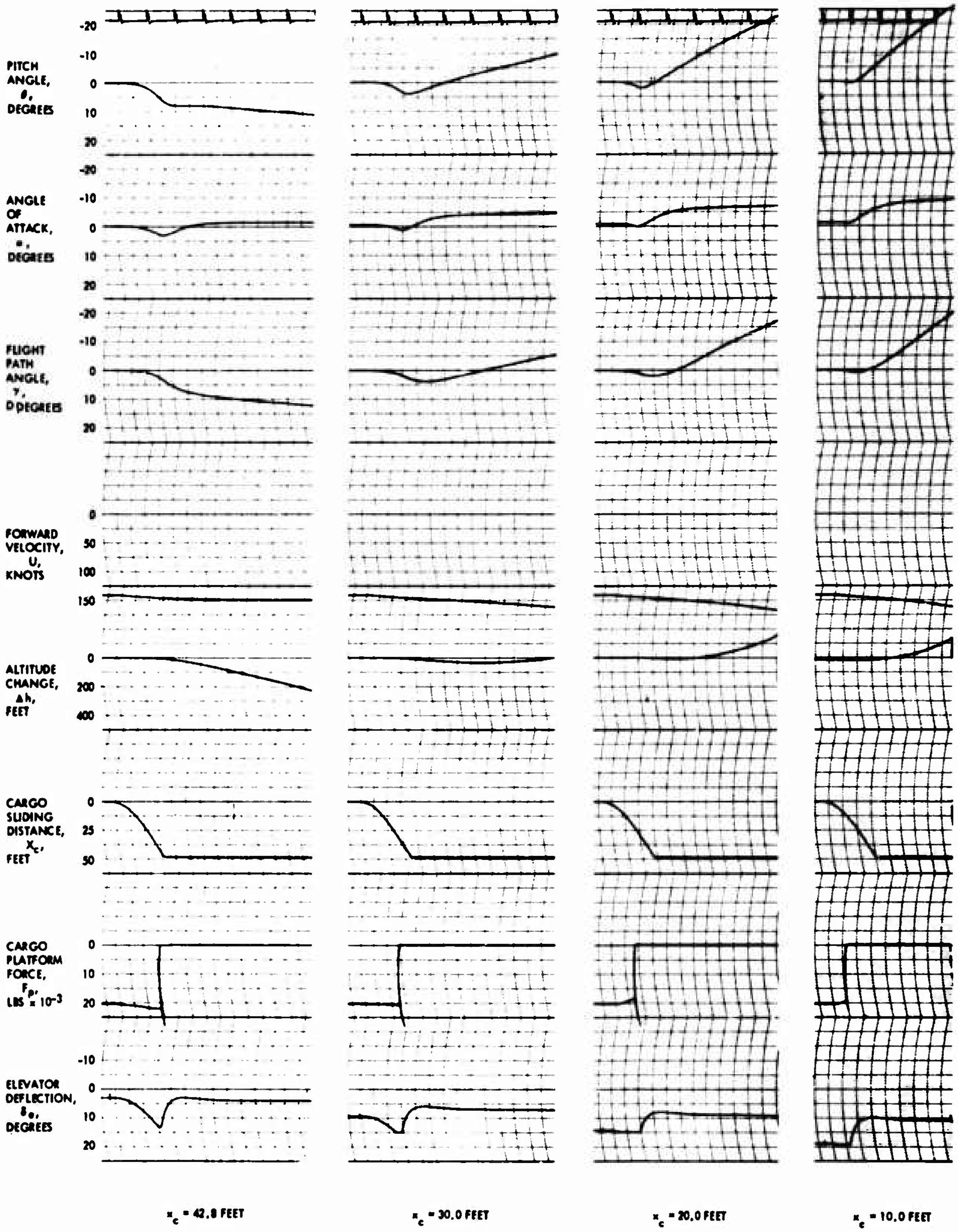


Figure 16A - Time Histories Showing the Effect of Decreasing the Cargo Sliding Distance in the Airplane, with Elevator Deflection

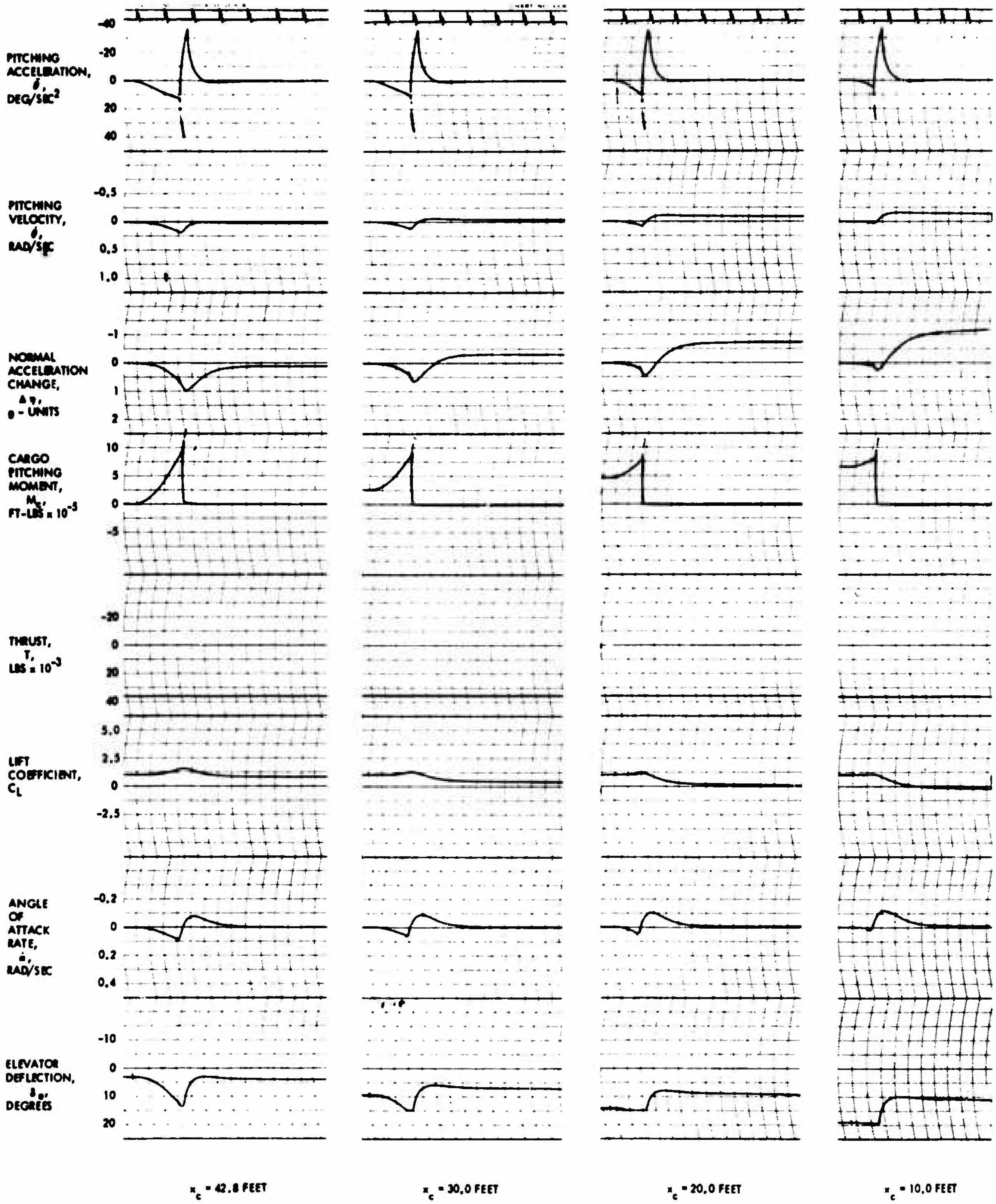


Figure 16B - Time Histories Showing the Effect of Decreasing the Cargo Sliding Distance in the Airplane, with Elevator Deflection

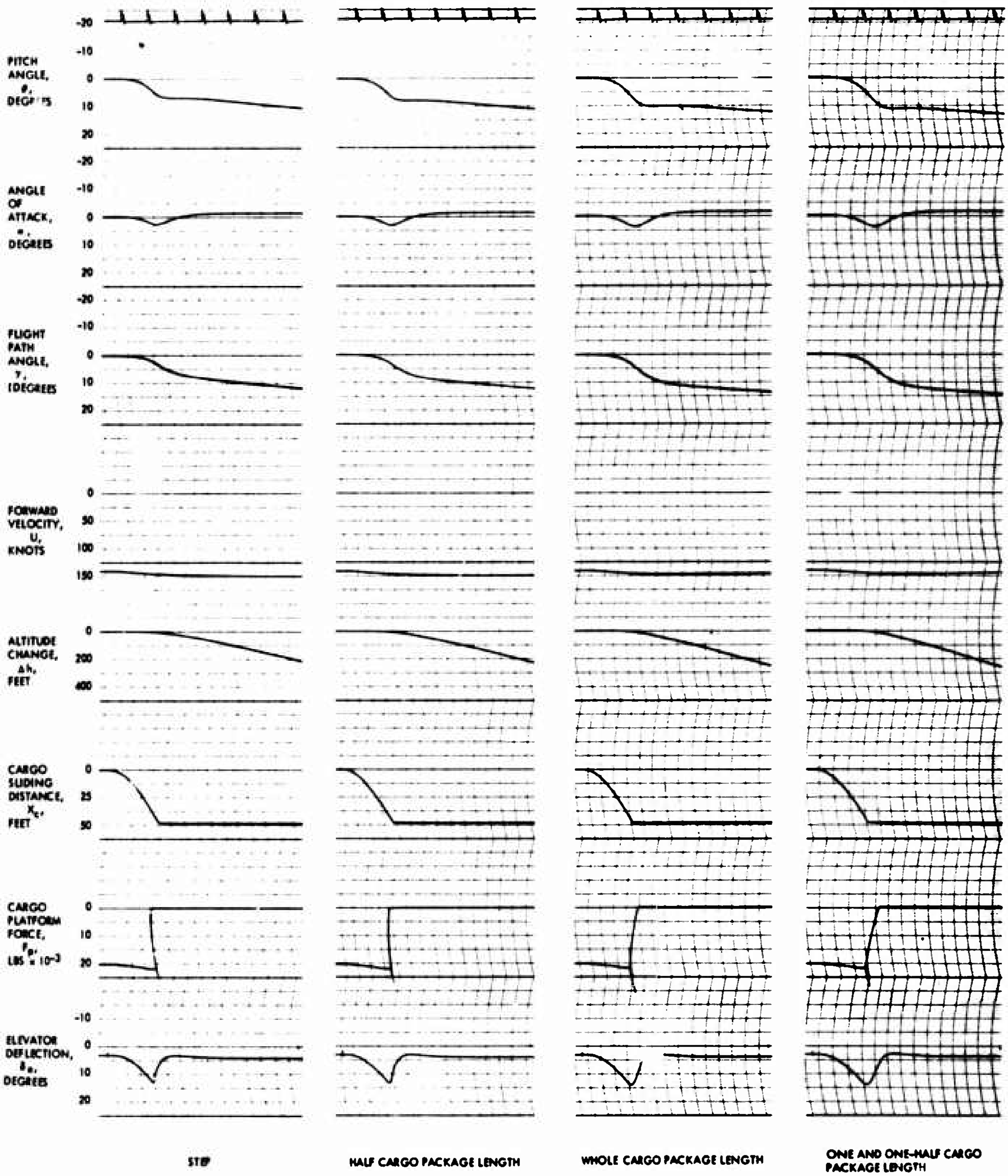


Figure 17A - Time Histories Showing the Effect of Tip-Off Type, with Elevator Deflection

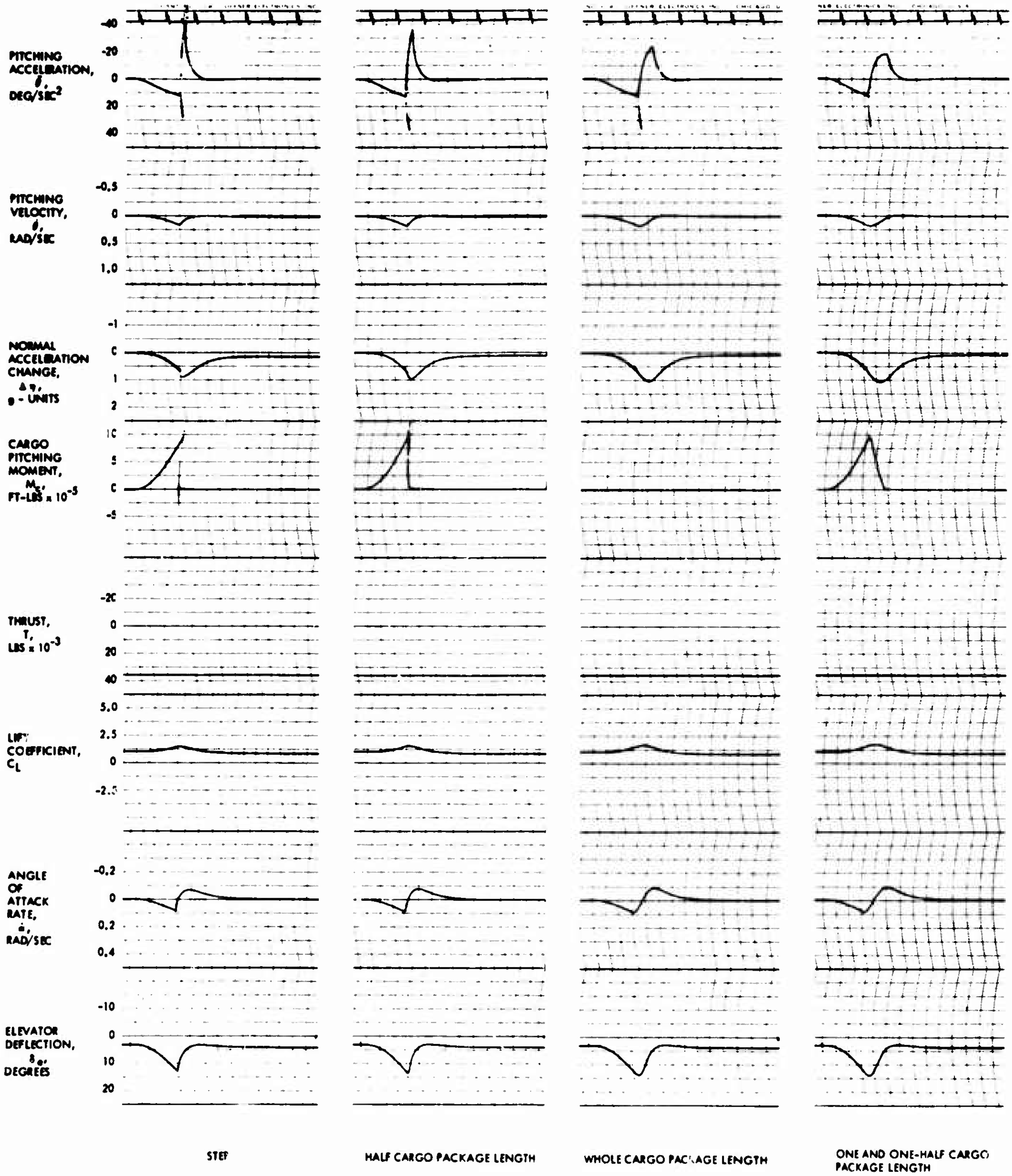


Figure 17B - Time Histories Showing the Effect of Tip-Off Type, with Elevator Deflection

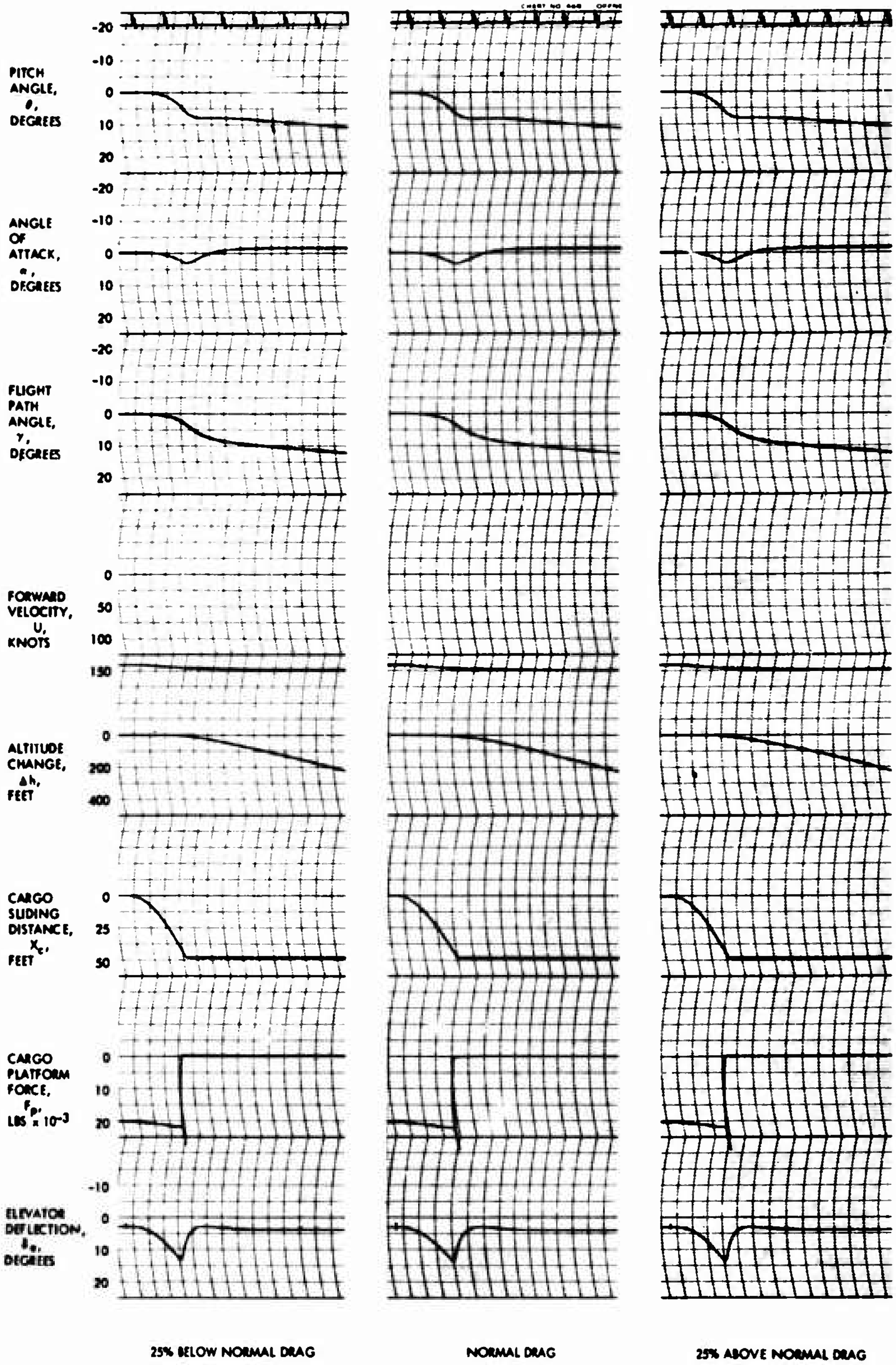


Figure 18A - Time Histories Showing the Effect of Changing Drag $\pm$ 25 Percent, with Elevator Deflection

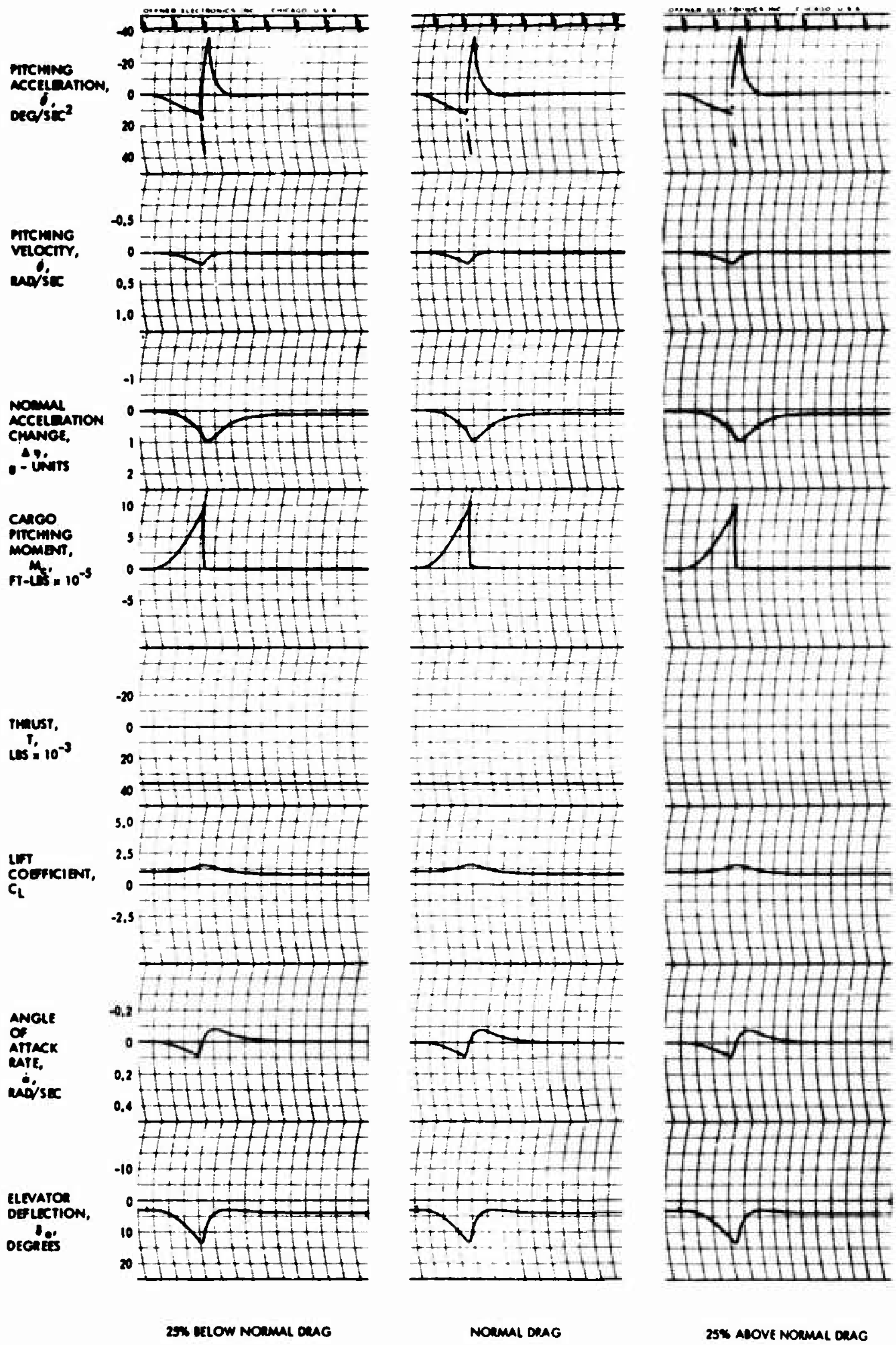


Figure 18B - Time Histories Showing the Effect of Changing Drag $\pm$ 25 Percent, with Elevator Deflection

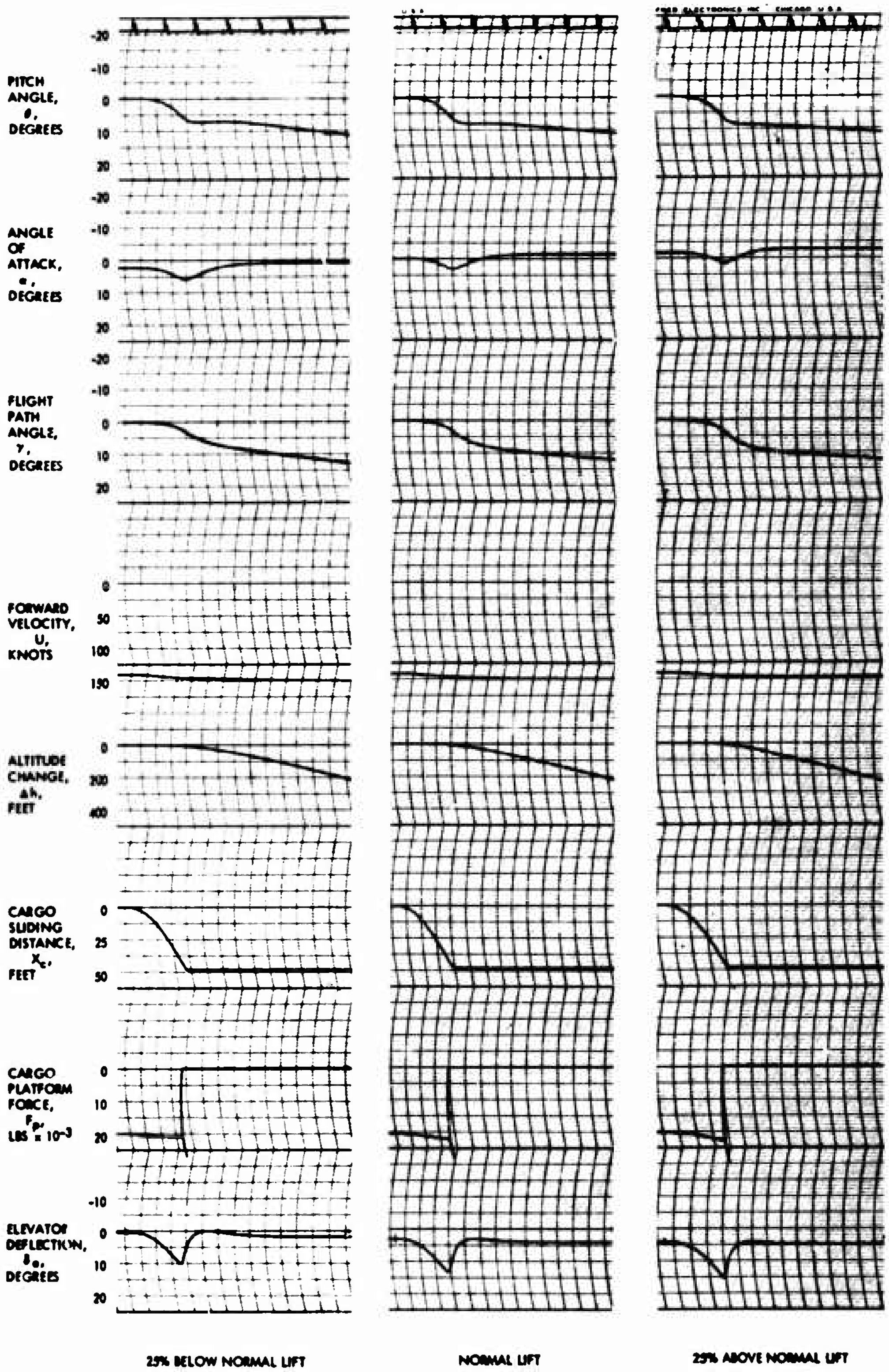


Figure 19A - Time Histories Showing the Effect of Airplane Lift ± 25 Percent, with Elevator Deflection

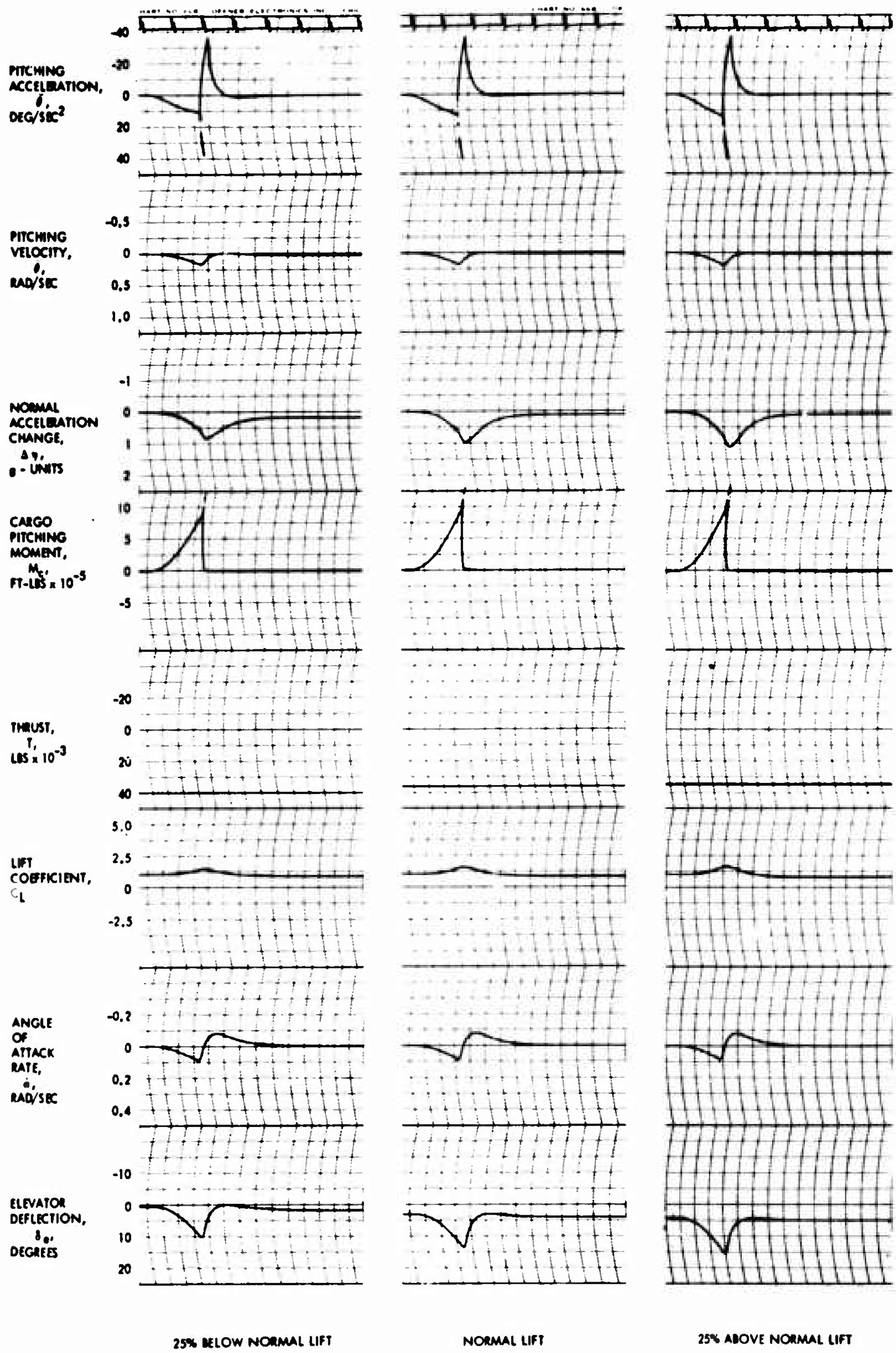


Figure 19B - Time Histories Showing the Effect of Airplane Lift $\pm$ 25 Percent, with Elevator Deflection

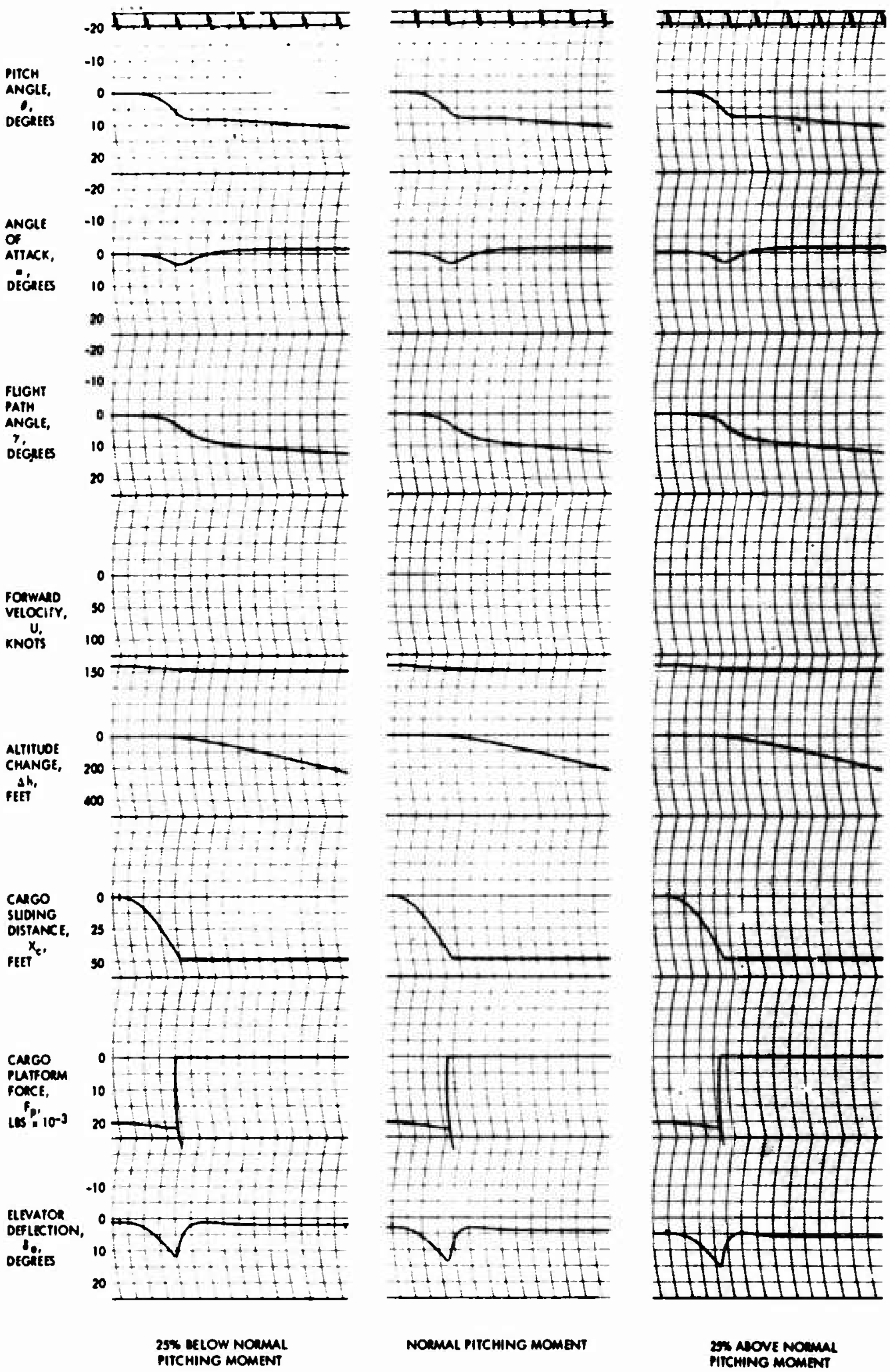


Figure 20A - Time Histories Showing the Effect of Changing Airplane Pitching Moment $\pm$ 25 Percent, with Elevator Deflection

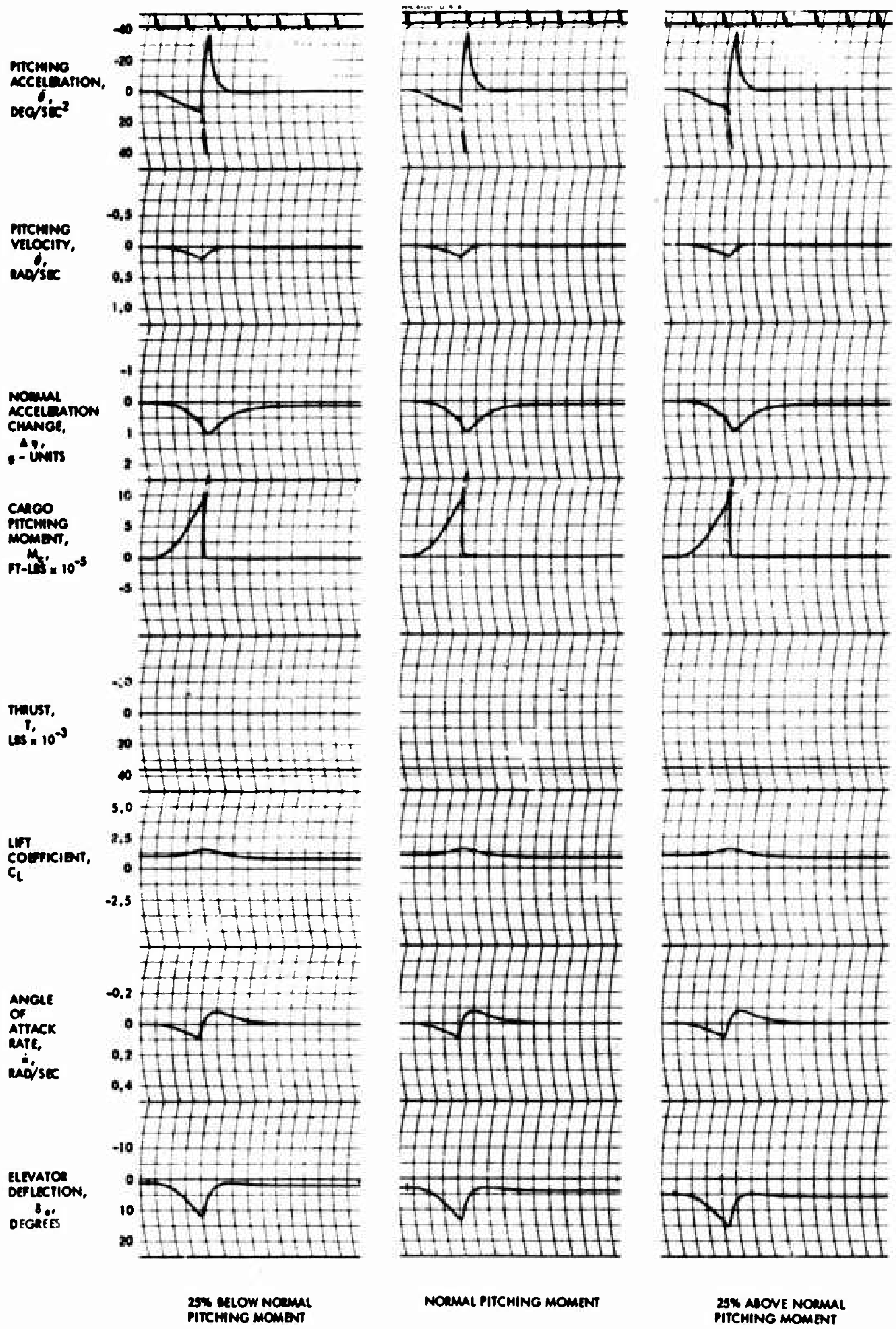


Figure 20B - Time Histories Showing the Effect of Changing Airplane Pitching Moment ± 25 Percent, with Elevator Deflection

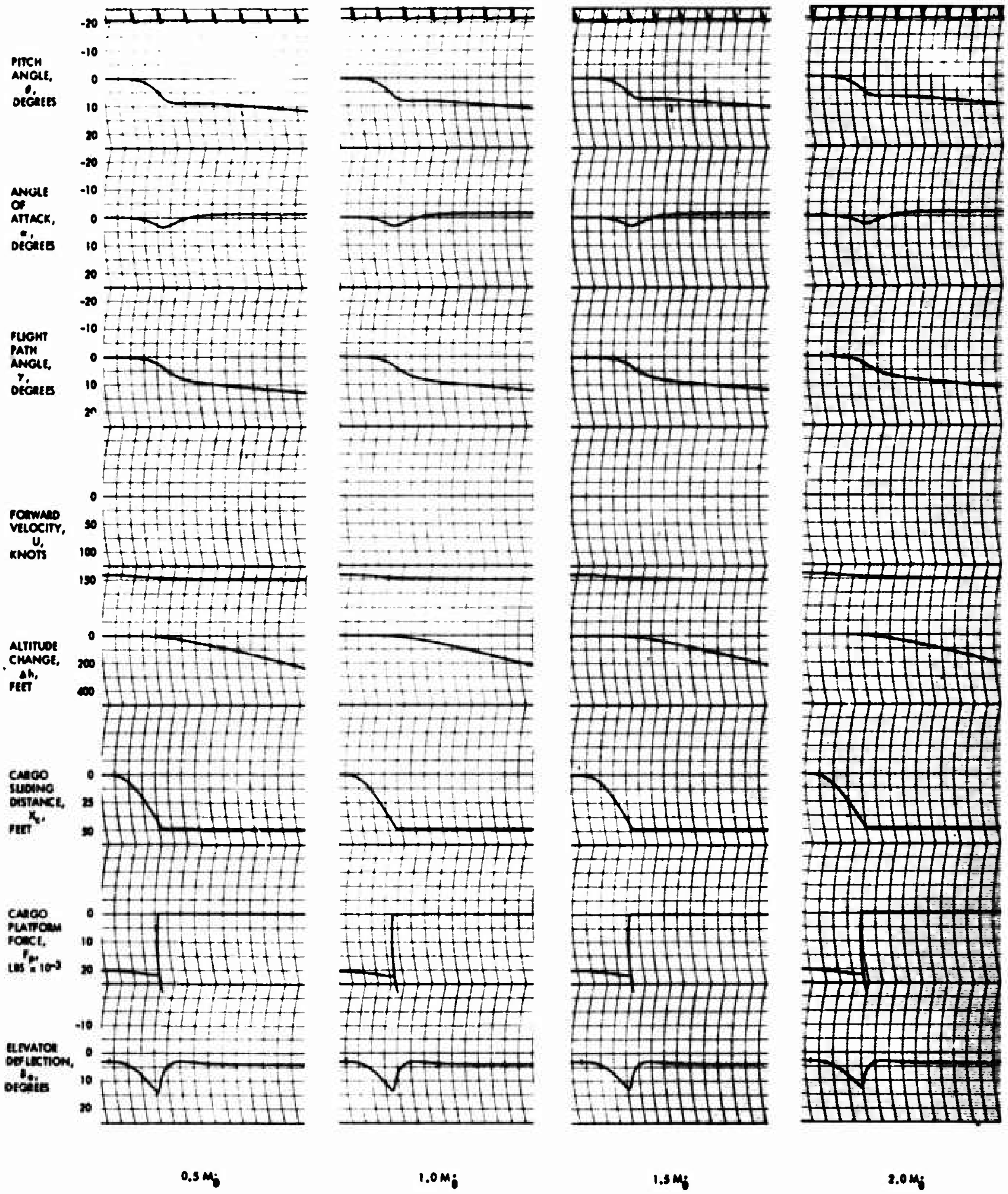


Figure 21A - Time Histories Showing the Effect of Increasing Pitch Damping, with Elevator Deflection

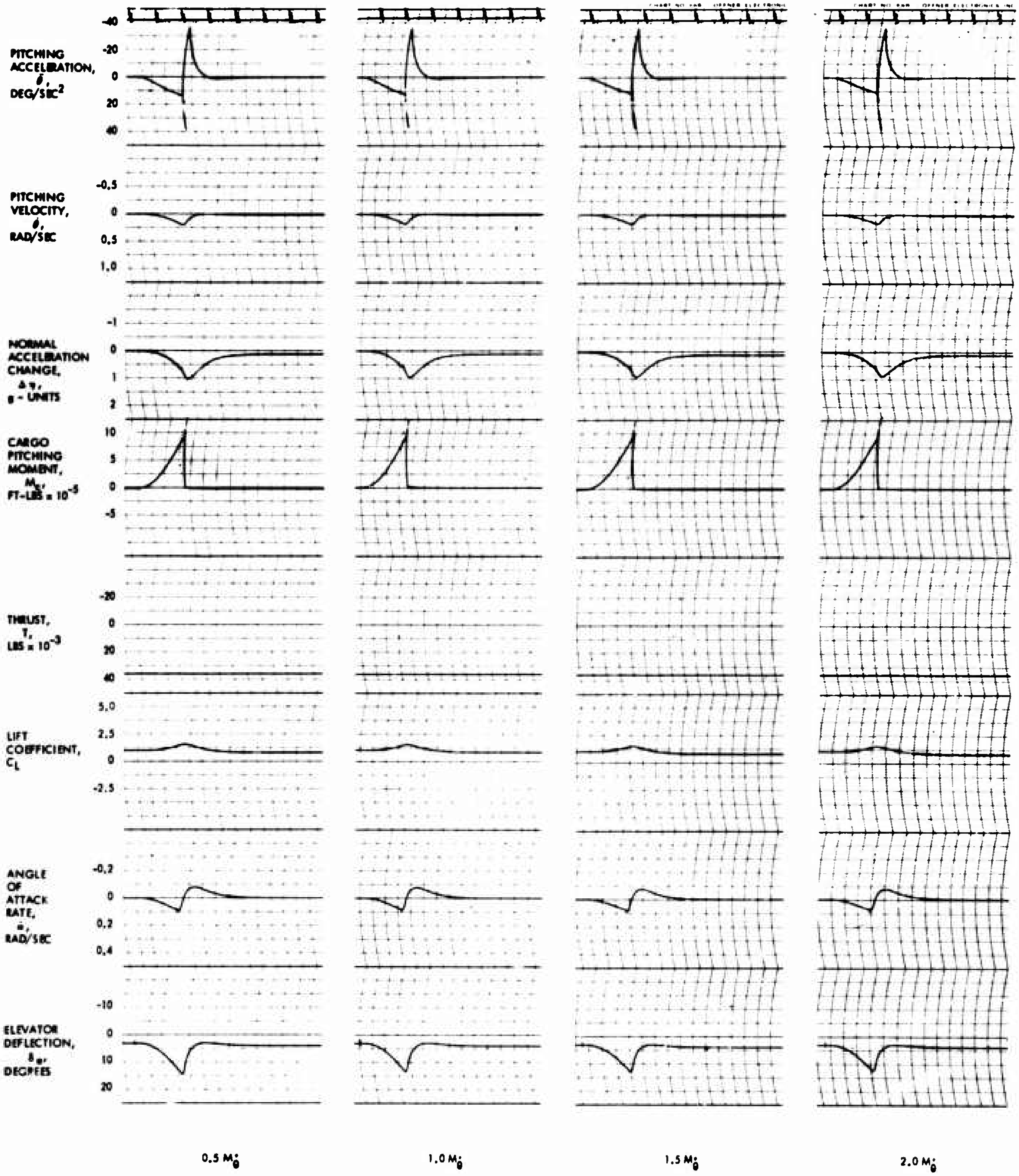


Figure 21B - Time Histories Showing the Effect of Increasing Pitch Damping, with Elevator Deflection

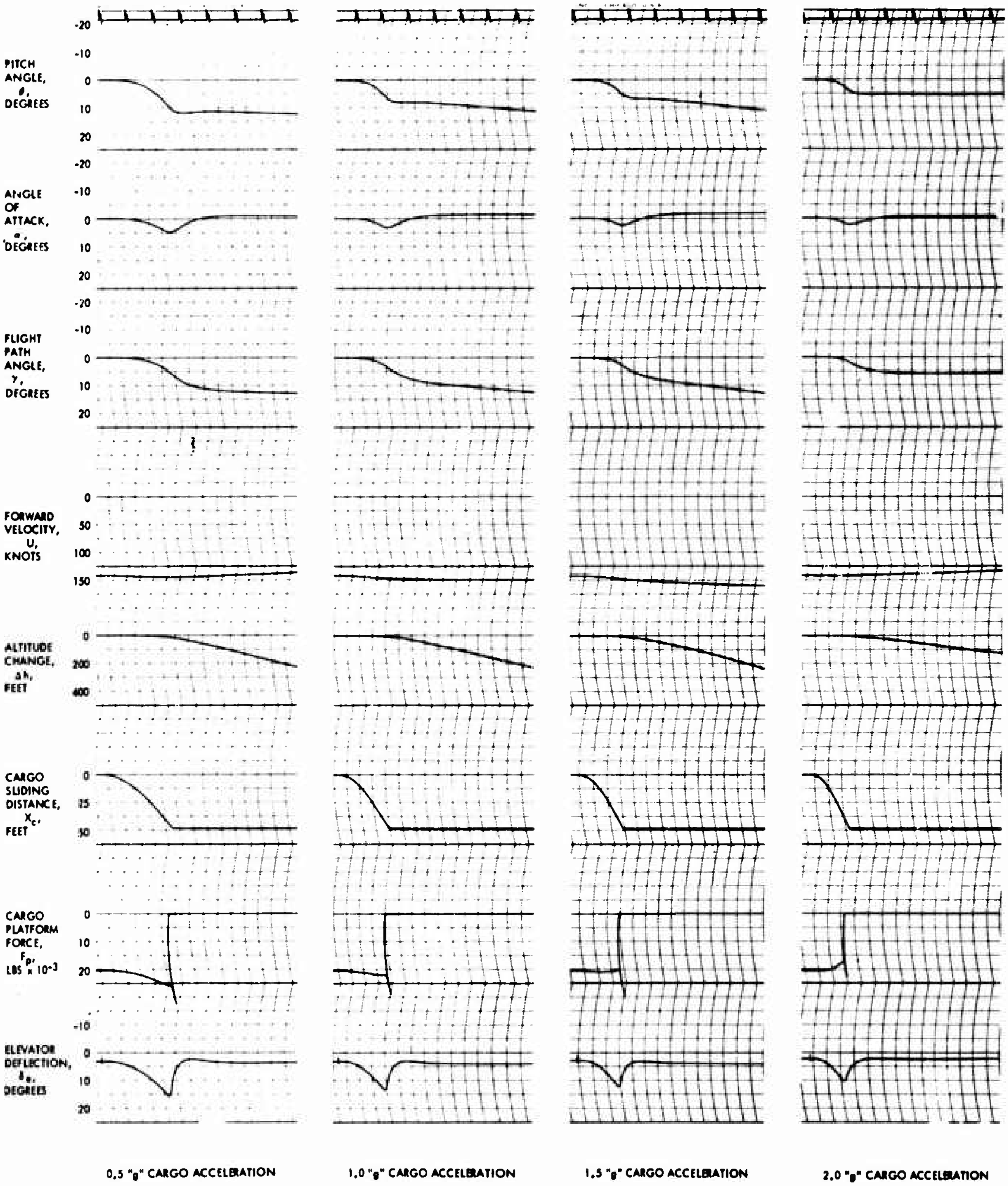


Figure 22A - Time Histories Showing the Effect of Increasing Cargo Acceleration, with Elevator Deflection

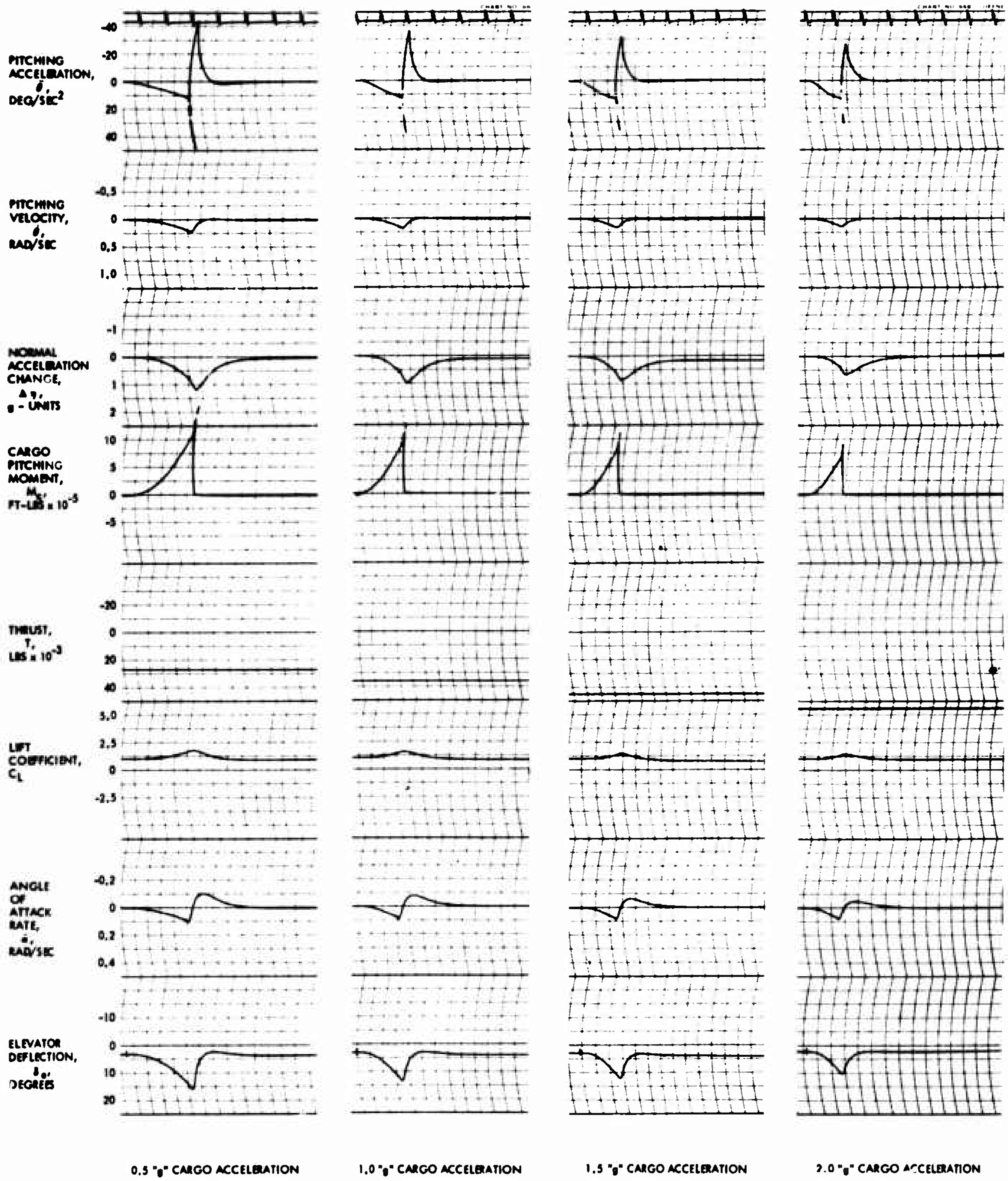


Figure 22B - Time Histories Showing the Effect of Increasing Cargo Acceleration, with Elevator Deflection

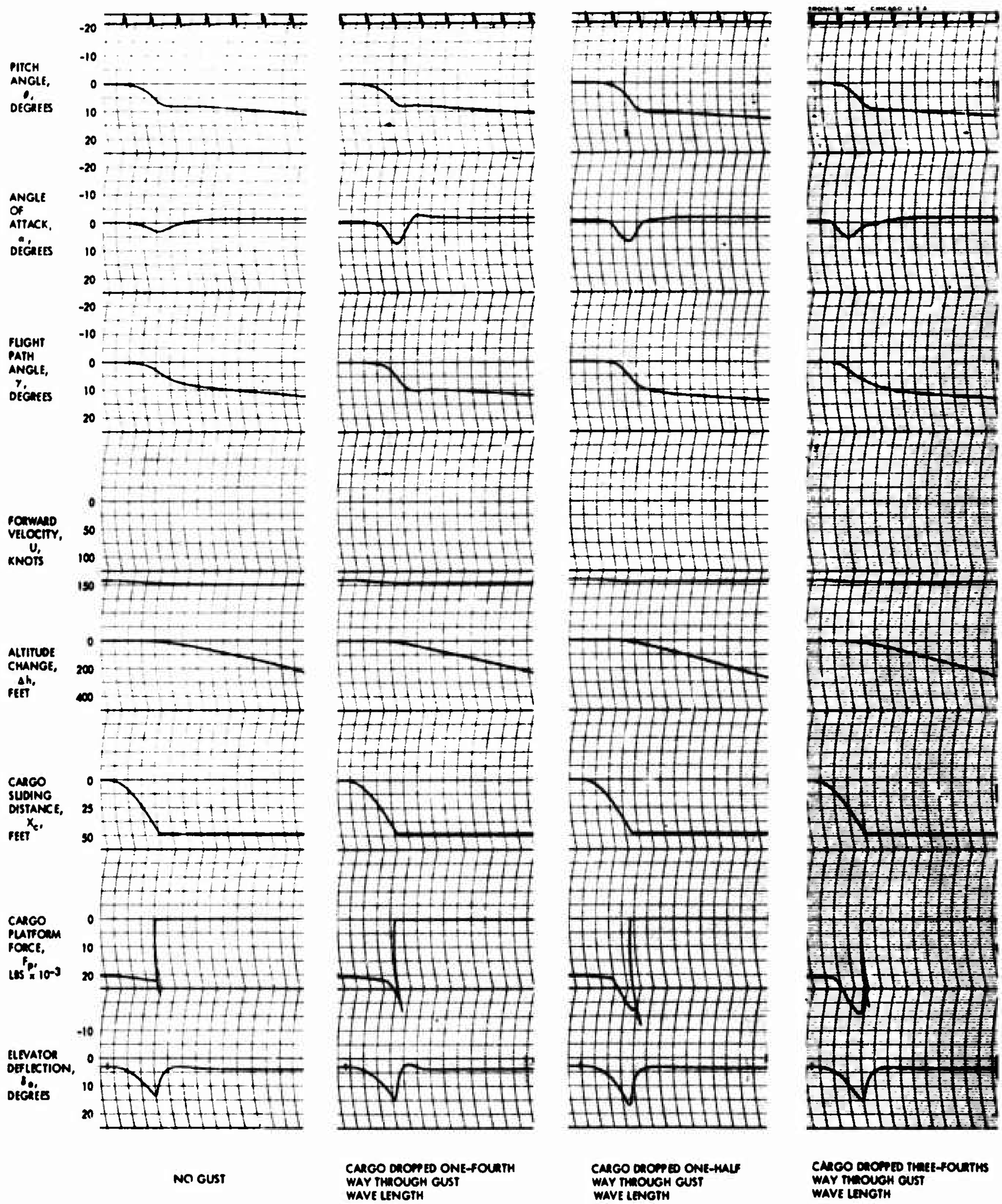


Figure 23A - Time Histories Showing the Effect of Airplane Response to a (1-cos) Gust, with Elevator Deflection

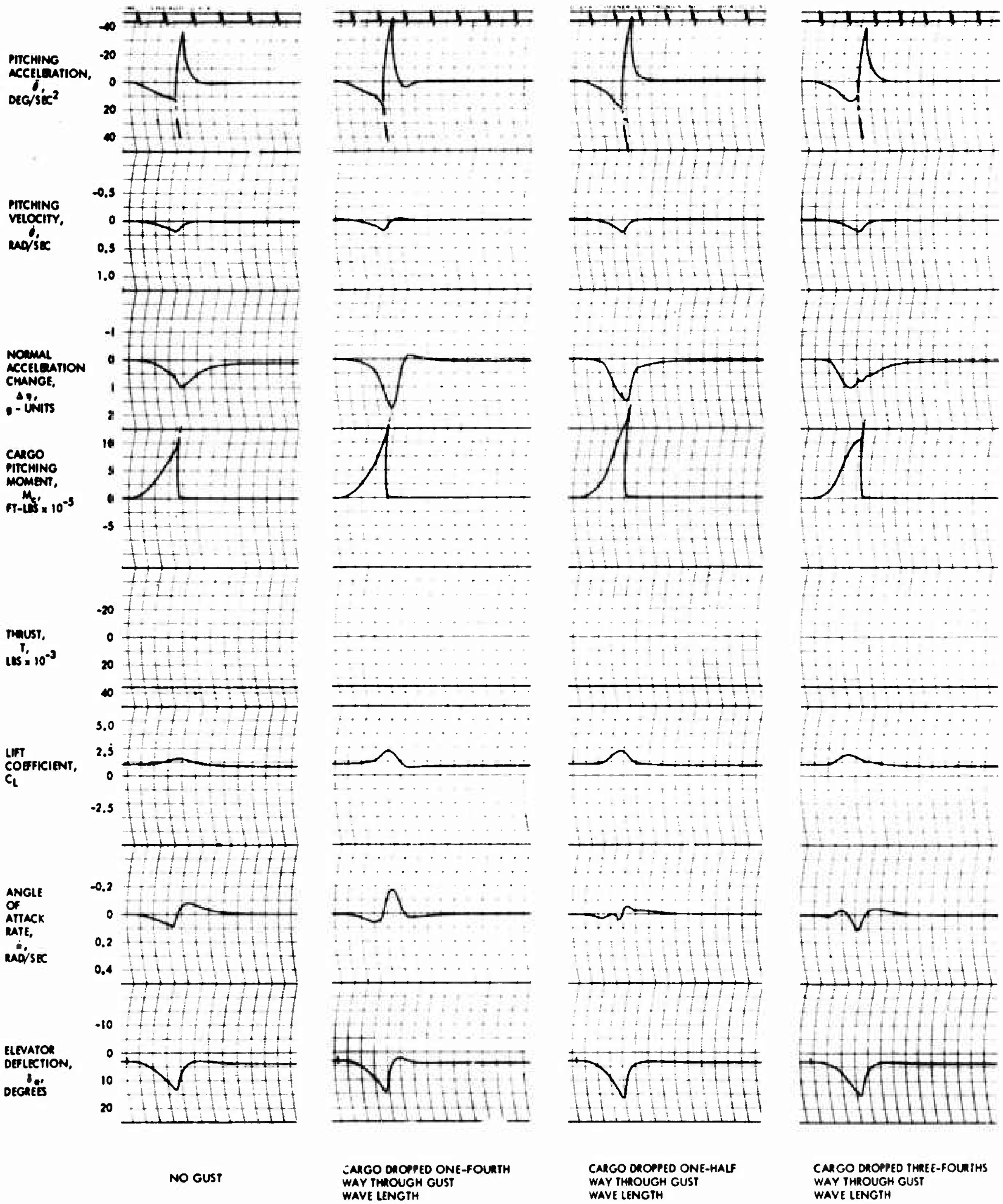


Figure 23B - Time Histories Showing the Effect of Airplane Response to a (1-cos) Gust, with Elevator Deflection

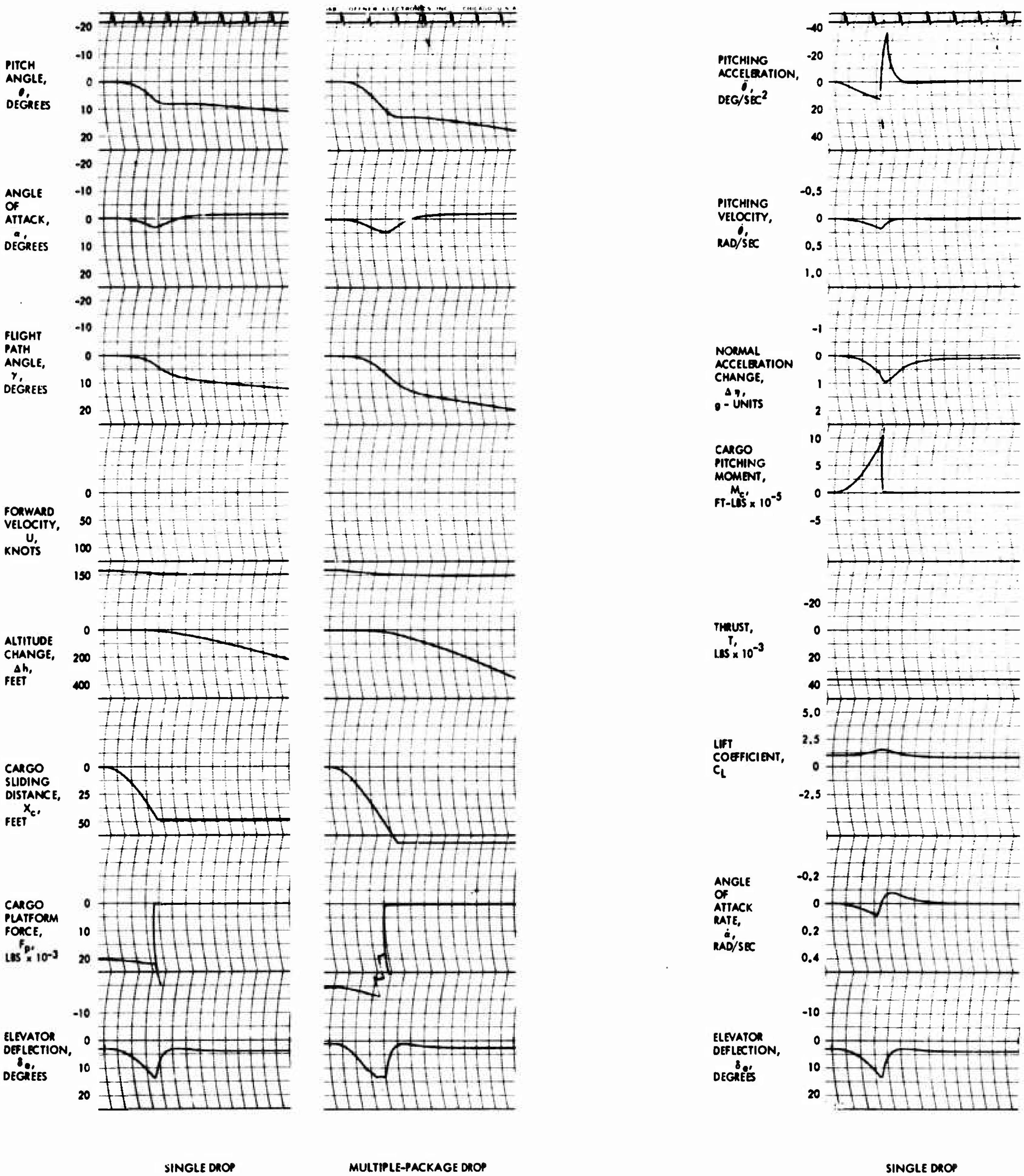
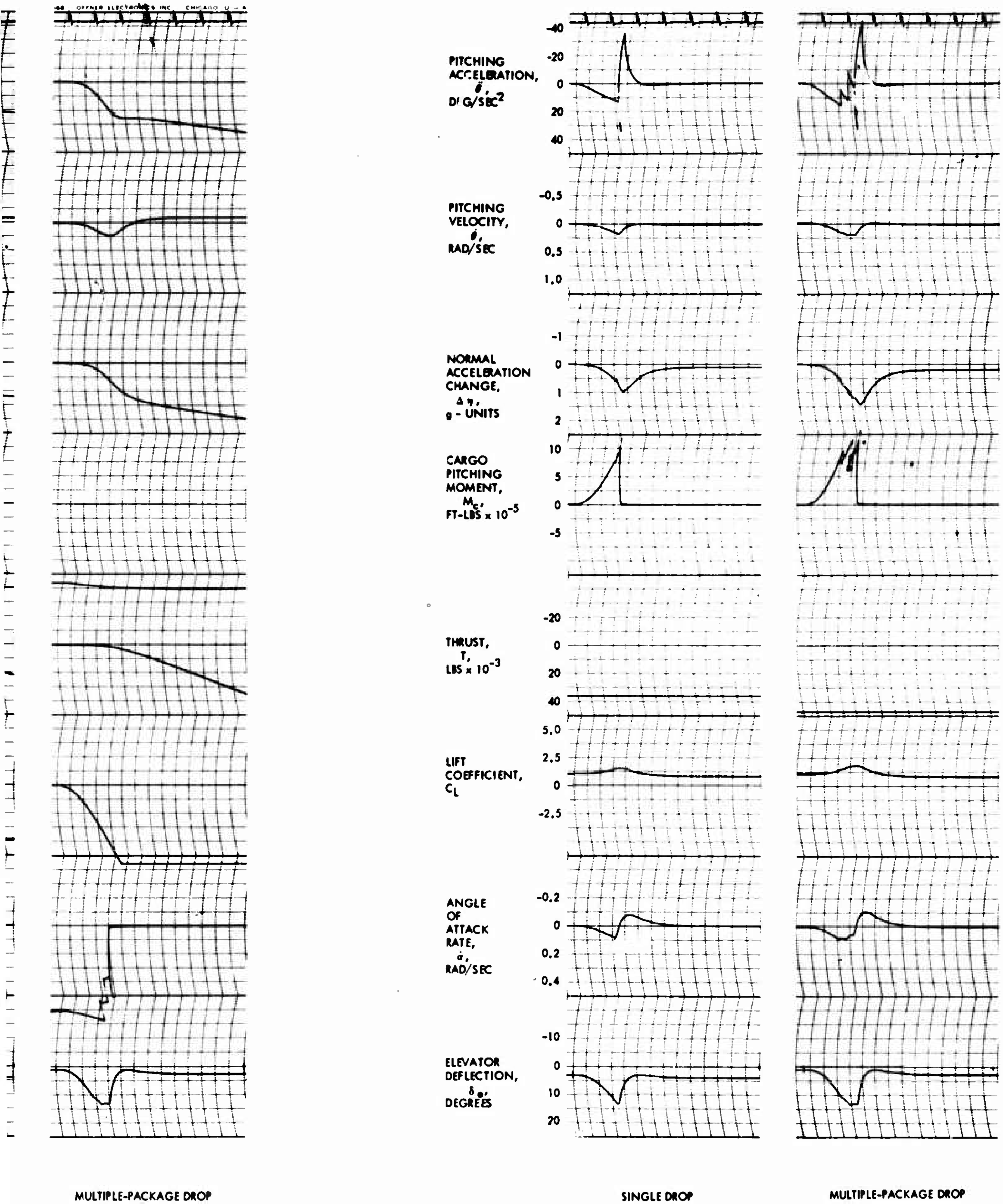


Figure 24 - Time Histories Showing the Effect of Multiple-Package Cargo Drops, with Elevator Deflection



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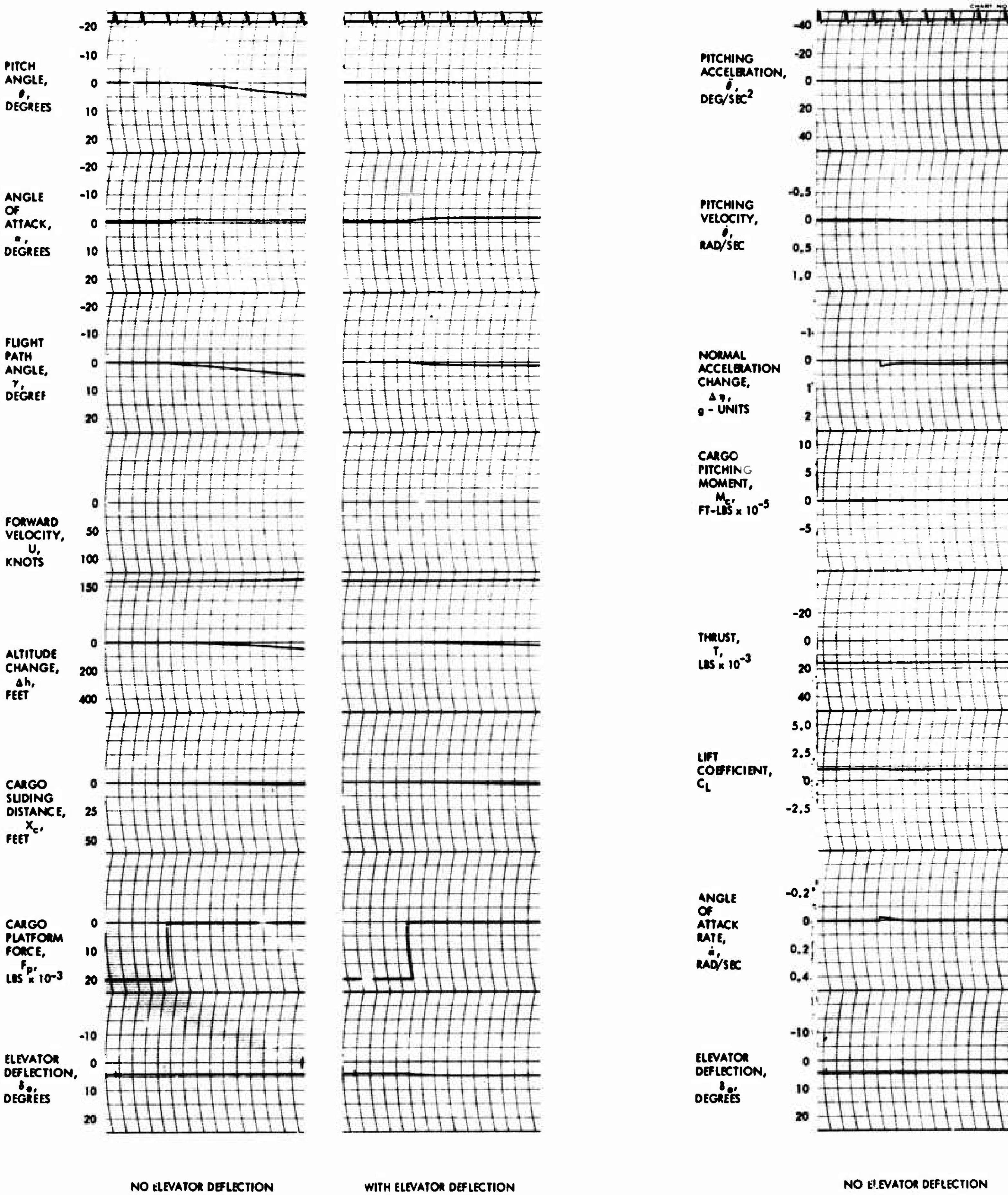
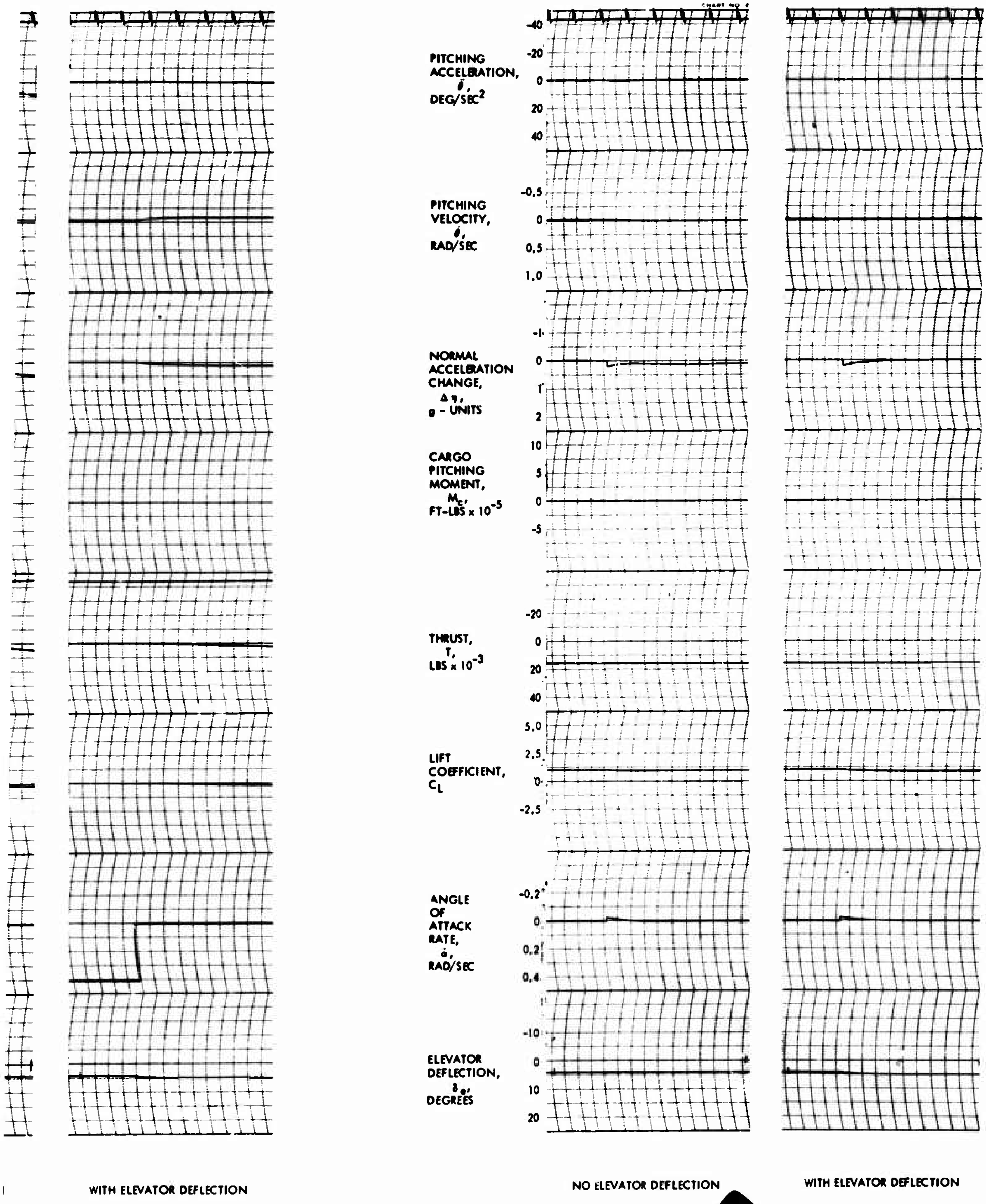


Figure 25 - Time Histories Showing Airplane Response to a Force-Down Ejection



Time Histories Showing Airplane Response to a Force-Down Ejection

CRITICALITY ANALYSIS OF PARAMETERS

The influence of the variations in forcing parameters on the response characteristics of the airplane can be visualized by scanning the time history plots of Figures 12 through 25. Each salient forcing parameter is discussed in the following paragraphs. However, to assist in interpretation of these influences and to provide data indicative of candidate forcing parameters for inclusion in the conceptual design of a simulator, cross-plots have been made of the peak values of angle of attack, incremental load factor, and pitching acceleration with variations in the forcing parameter. Two values are shown for pitching acceleration. The positive values represent the nose-up pitching which occurs while the cargo is being extracted, while negative values represent the nose-down pitching indicative of recovery. Angle of attack was selected for cross-plot inasmuch as flight path angle and pitch angle did not always achieve either a peak or a stable value. The cross-plots include the effect of elevator deflection where considered necessary to show trends.

Forcing Parameters

Cargo Weight

Four cargo weights were investigated and the results are shown in Figures 12 and 13. The effects of increasing the cargo weights of 3000, 10,000, 15,000, and 20,000 pounds at a 1.0 g extraction rate is seen by reading the time histories from left to right. The most significant changes, as shown in Figures 12 and 13, occur in the flight path angle, pitching acceleration, normal acceleration, and cargo pitching moment. The flight path angle is a function of both pitch angle and angle of attack which cause the large flight path angle change. The data of Figure 12 suggest that elevator deflection should be used when extracting cargos of large weight relative to airplane total weight. Figure 13 shows a marked decrease in γ , Δn, and M_c as corrective elevator is applied but $\ddot{\theta}$ does not decrease as much since this parameter is directly a function of M_c. A cross-plot of the data of Figures 12 and 13 is given in Figure 26.

Increasing the cargo weight for drop increases the incremental load factor on the airplane, thereby limiting the amount of cargo that can be dropped. However, corrective elevator deflection can increase the droppable cargo weight, thus extending the effectiveness of the airplane. Note that this parameter did not change the damping characteristics of the airplane.

Forward Velocity

Figure 14 shows the effect of increasing the initial forward velocity. The speed was increased from 100 to 220 knots in 40-knot increments, and

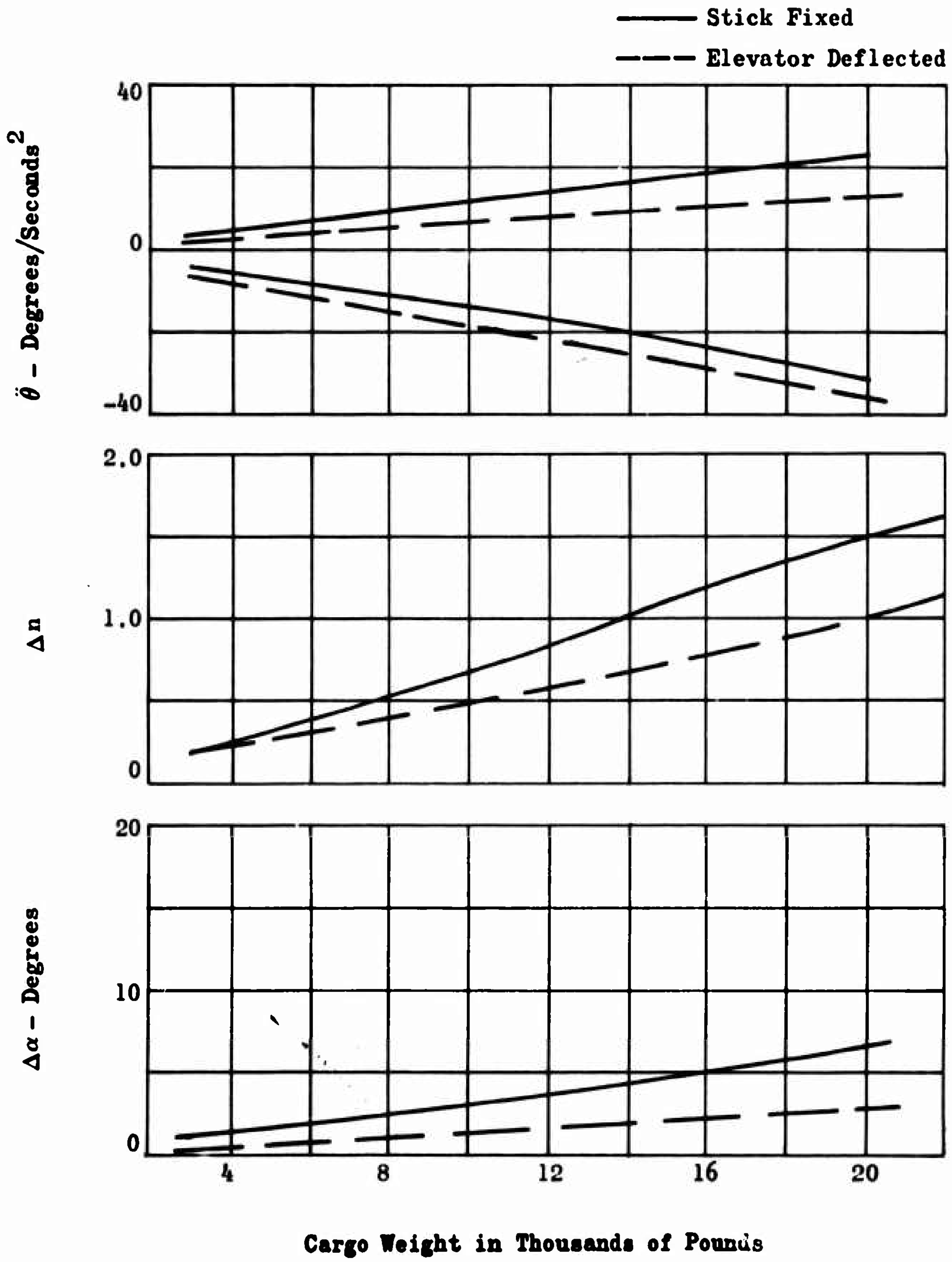


Figure 26 - Effect of Varying Cargo Weight

the results are shown in Figure 14. A cross-plot of the data is given in Figure 27.

Increasing the forward velocity decreased the overall flight path angle but markedly increased the pitching and normal acceleration. Attention is drawn to the angle-of-attack trace. At 100 knots it was impossible to fly the C-130 at zero degree angle of attack; therefore, a realistic flight condition was chosen at this speed. Increasing the airplane velocity while extracting the cargo at constant-g increases the normal acceleration and in this case exceeded the limit load factor by half a "g". However, using corrective elevator readily reduced the incremental load factor so that the peak values were approximately the same. The platform force traces, F_p, show a reverse trend when increasing the forward speed. This trend is reasonable because at the lower speed the pitching acceleration peaks before the cargo leaves the airplane. The airplane is also flying near the stall region.

Center of Gravity

The effects of center-of-gravity position are shown in Figure 15. Four values were selected to provide a variation from the most forward to the most aft for the C-130 at the gross weight of 100,000 pounds. Changing the airplane center of gravity changes the static stability of the airplane because of the change in the slope of the pitching moment versus angle of attack curve. A shift of center of gravity from forward to the aft position primarily affects the pitch angle time history. The other traces do not vary appreciably but the pitch angle trace shows the influence because of a change in damping. Corrective elevator deflection reduces γ and Δn, but it will be noted that limit deflection was reached. As the center of gravity moves aft, the elevator deflection required for trim increases which means less elevator power is available to offset the moment due to the cargo sliding aft. However, no adverse conditions were encountered.

The conclusion indicated by the effect of variation in center of gravity shown in Figure 28 is that center-of-gravity position is not very critical provided its initial position is within the allowable center-of-gravity limits of the airplane.

Cable Angle

In this study, cable angle is defined as that angle between the horizontal and the cargo extraction force. In the mathematical analysis, the cable angles were varied over a range of 25 degrees. The four angles used for this investigation were -10, 0, 10, and 15 degrees. It was considered that this range was adequate since the cargo floor was level with the ground and the only other factor that would influence this angle would be the airflow over the aft end of the airplane body.

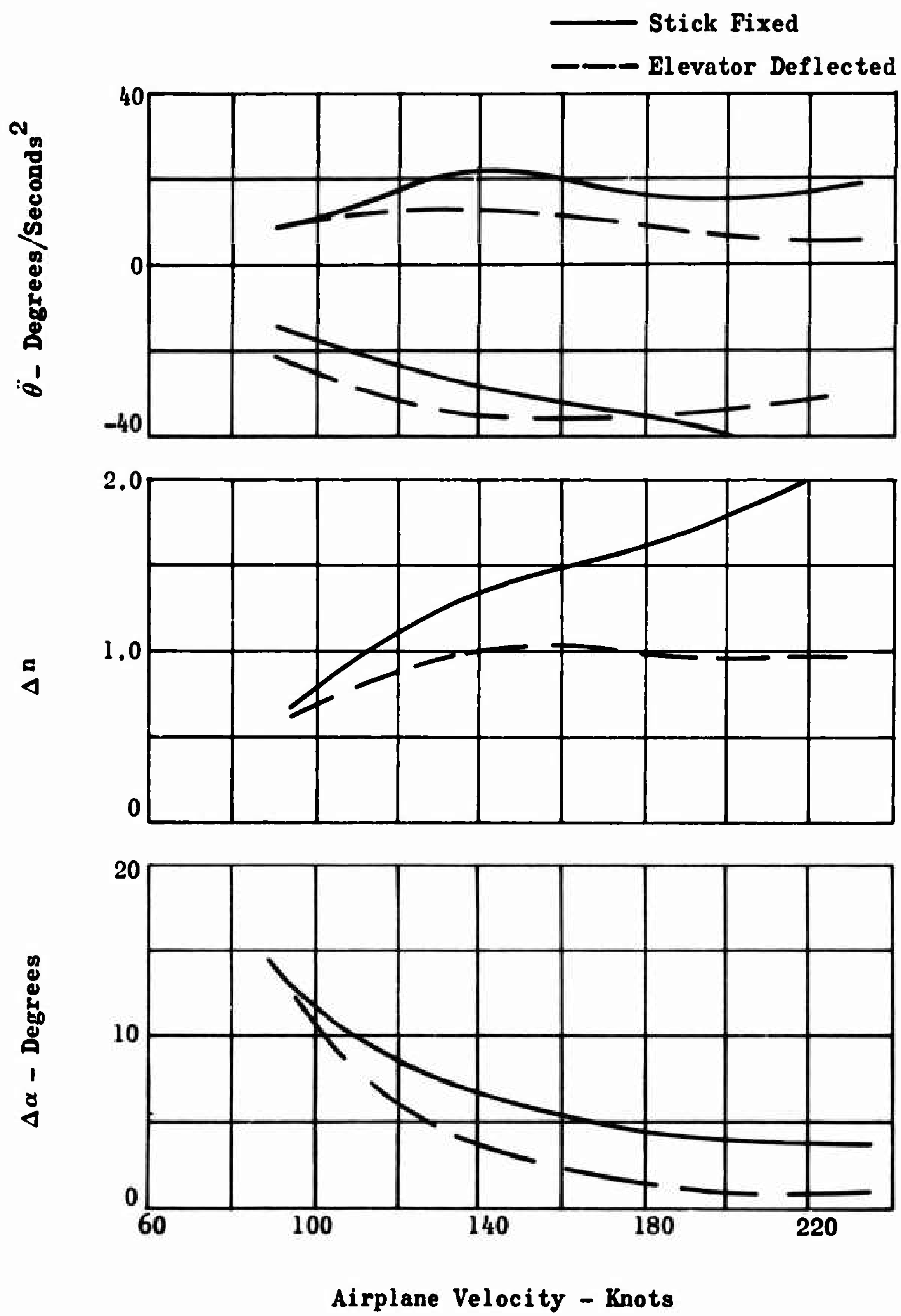


Figure 27 - Effect of Varying Airplane Velocity

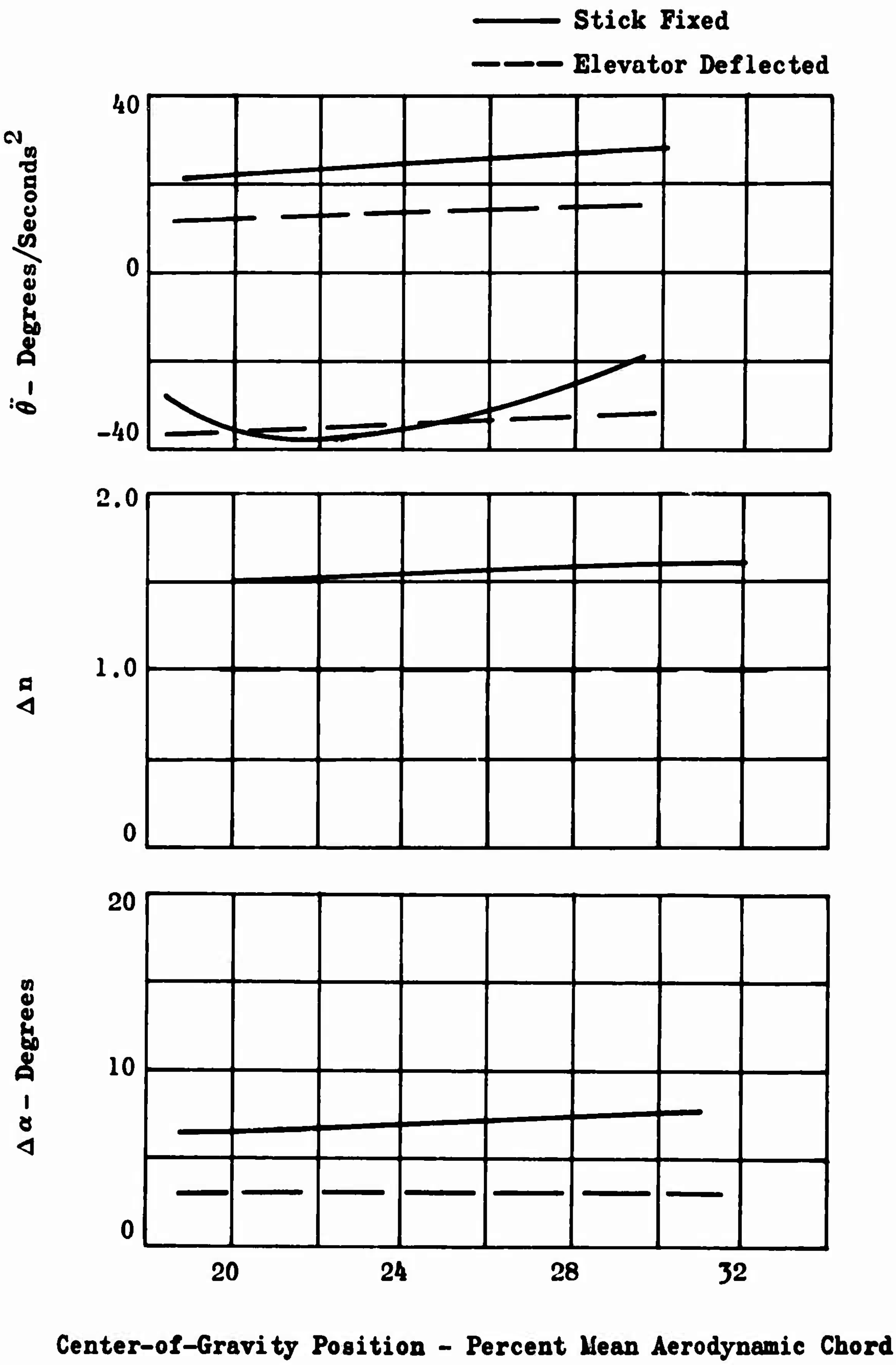


Figure 28 - Effect of Varying Center of Gravity Position

Over the range of cable angles considered, airplane response does not change significantly, as shown by Figure 29, and therefore this parameter is not considered to be critical.

Cargo Sliding Distance

The distance the cargo must travel in the airplane before clearing the ramp door lip causes significant changes in pitching moments which, in turn, cause large changes in flight path angle. Figures 16 and 30 show radical changes in some of the flight parameters due to length of travel of the cargo. Reading from left to right in Figure 16 shows the flight characteristics of the airplane as affected by the sliding distance, x_c. As this distance was decreased, the elevator was retrimmed to offset the increase in static nose-up pitching moment. During extraction, the shorter the slide distance the smaller the change in flight characteristics. This is true until nose-down pitch occurs at which time it is evident that corrective elevator must be applied. Caution must be used when interpreting the x_c trace, which should be read in conjunction with the F_p trace in order to determine the distance the cargo traveled. Because of the increase in complexity of wiring, the x_c trace was not restrained. However, the distance can be read by referring to the F_p trace and noting the time at which the cargo left the airplane and then by applying this time to the x_c trace. When corrective elevator was applied, the response was not as marked, but the airplane did continue to pitch nose-down when adequate elevator travel was still available as shown in Figure 30. This fact is due to the simple autopilot used in the analysis. Operation depended upon the pitching velocity, and as soon as quantity assumed a steady state value no more elevator was required. Therefore, nose-down pitch continued. It is concluded that the distance the cargo travels in an airplane has a very marked bearing on the magnitude of the resultant flight response.

Tip-Off Effectiveness

Tip-off is a term coined to describe the variation in pitching moment as the cargo passes the ramp door lip. The assumption was made in this study that an average package would weigh about 1000 pounds per foot. As this 20-foot package passed over the ramp door lip, analysis was made assuming four different tip-off types: 1) M_c became zero the instant the cargo package center of gravity passed the lip; 2) M_c decreased linearly to zero from the time the center of gravity reached the lip until it was 10 feet past the lip; 3) 15 feet past the lip; and 4) 20 feet past the lip. The resulting time histories of Figure 17 indicate an increase in γ and a slight increase in the peak value of Δn.

Corrective elevator deflection was significant because it markedly increased the flight path angle. The fact that the M_c trace for the 15-foot tip-off length using corrective elevator did not record was a function of the recorder alone and does not void the other traces.

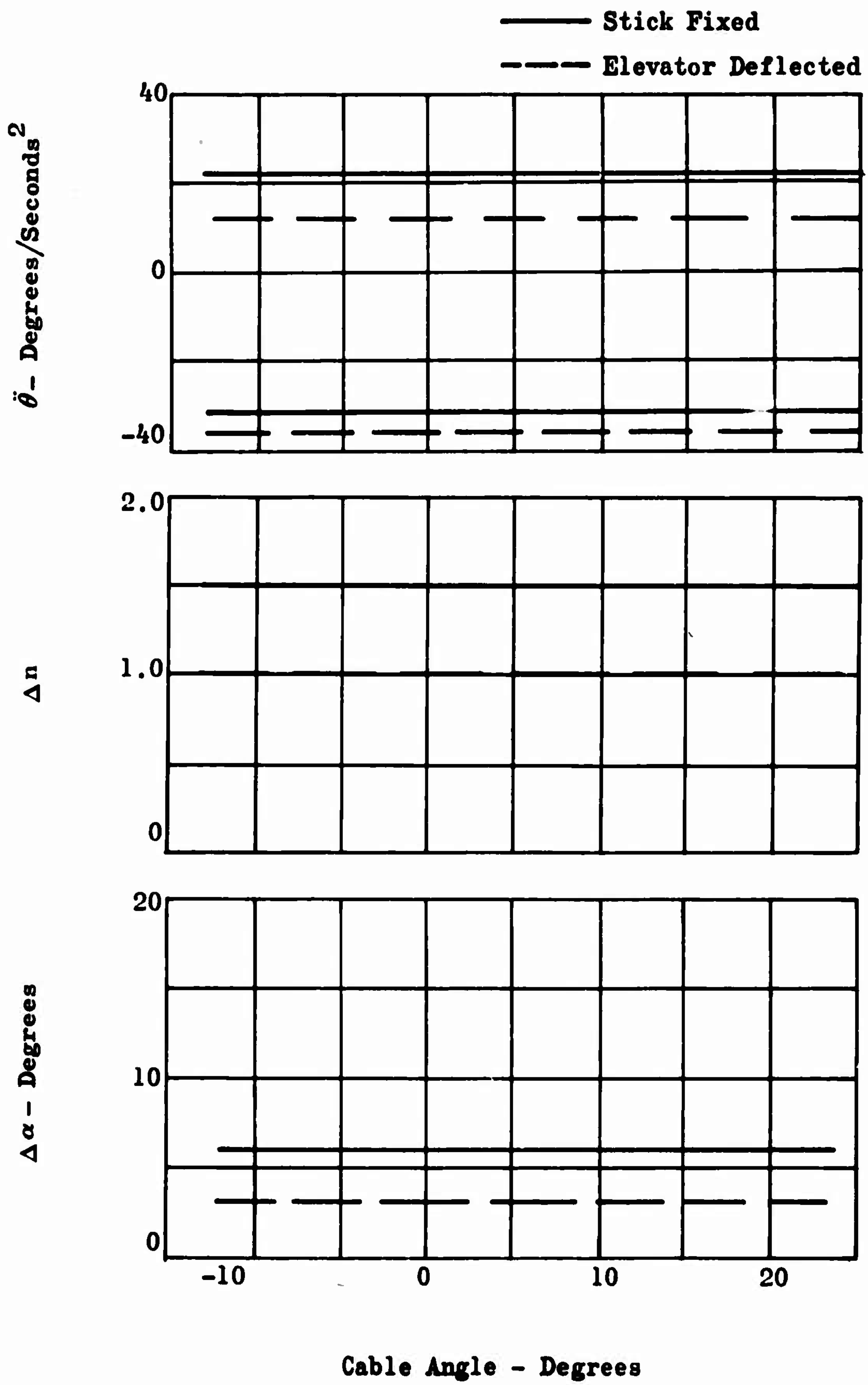


Figure 29 - Effect of Varying Cable Angle

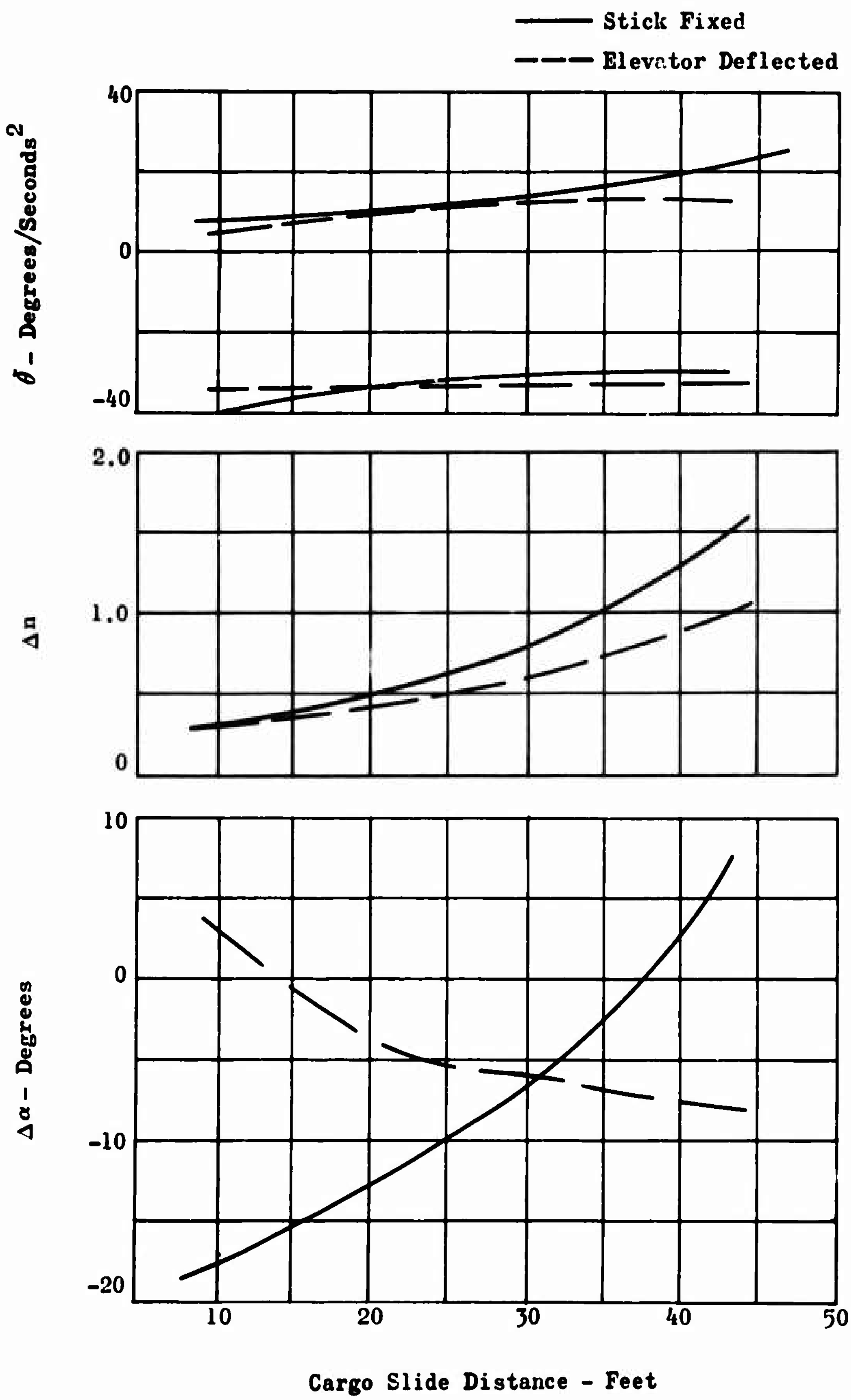


Figure 30 - Effect of Varying Cargo Slide Distance

Increasing the tip-off distance does not seriously influence the flight characteristics as summarized by Figure 31, but from past experience, treatment of this phenomenon does achieve closer correlation between analog traces and flight test results.

Drag Effectiveness

In order to estimate the effect of changing the airplane drag characteristics, the C-130 drag curve was both increased and decreased by 25 percent. A detailed examination of Figure 18 shows that no significant change occurs in flight characteristics due to the change in drag curves investigated. Accordingly, these data have not been cross-plotted.

Lift Effectiveness

Lift effectiveness was investigated in the same manner as the drag effectiveness. Figure 19 shows the effect of a $\pm$ 25 percent change in lift, and the results are summarized in Figure 32. As the lift increases, the flight path angle and normal acceleration also increase. Over the 1965-75 period, it is concluded that the lift characteristics as shown will not affect airplane response more than the small changes shown.

Pitching Moment Effectiveness

Figure 20 shows the $\pm$ 25 percent change in pitching moment, and the results are summarized in Figure 33. Virtually no change in airplane response that is due to altering the aerodynamic pitching moment over this range is recorded.

Pitch Damping

The effects of airplane damping in pitch are shown in Figure 21. The range covered consisted of decreasing this parameter to 0.5 times its original value and, alternatively, increasing it first to 1.5 times its original value and then to 2.0 times its original value. This wide range of variation shows little effect on aircraft response. The peak pitching velocity and normal acceleration decrease slightly when M_θ increases; altitude change also decreases. The inherent damping characteristics of an airplane help to establish the flight response, and there are occasions when this damping must be artificially increased as much as tenfold. This would require a pitch damper. The effect of the variation is summarized in Figure 34.

Angle-of-Attack Damping

Angle-of-attack damping furnishes a very small amount of damping, and analysis of the time history traces indicated that it has a very small influence on airplane response. Accordingly, these data are not summarized in a cross-plot.

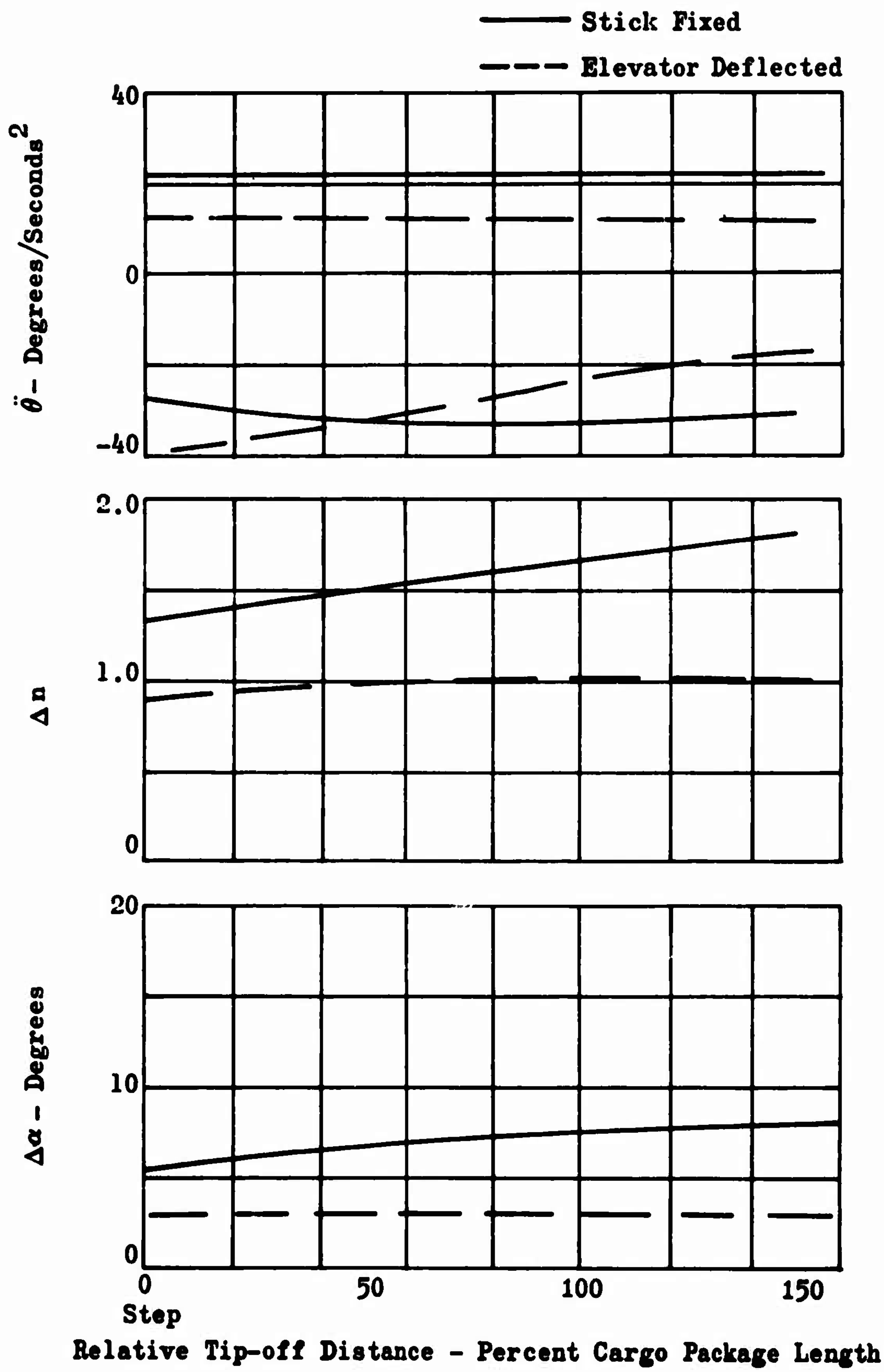


Figure 31 - Effect of Varying Tip-Off Distance

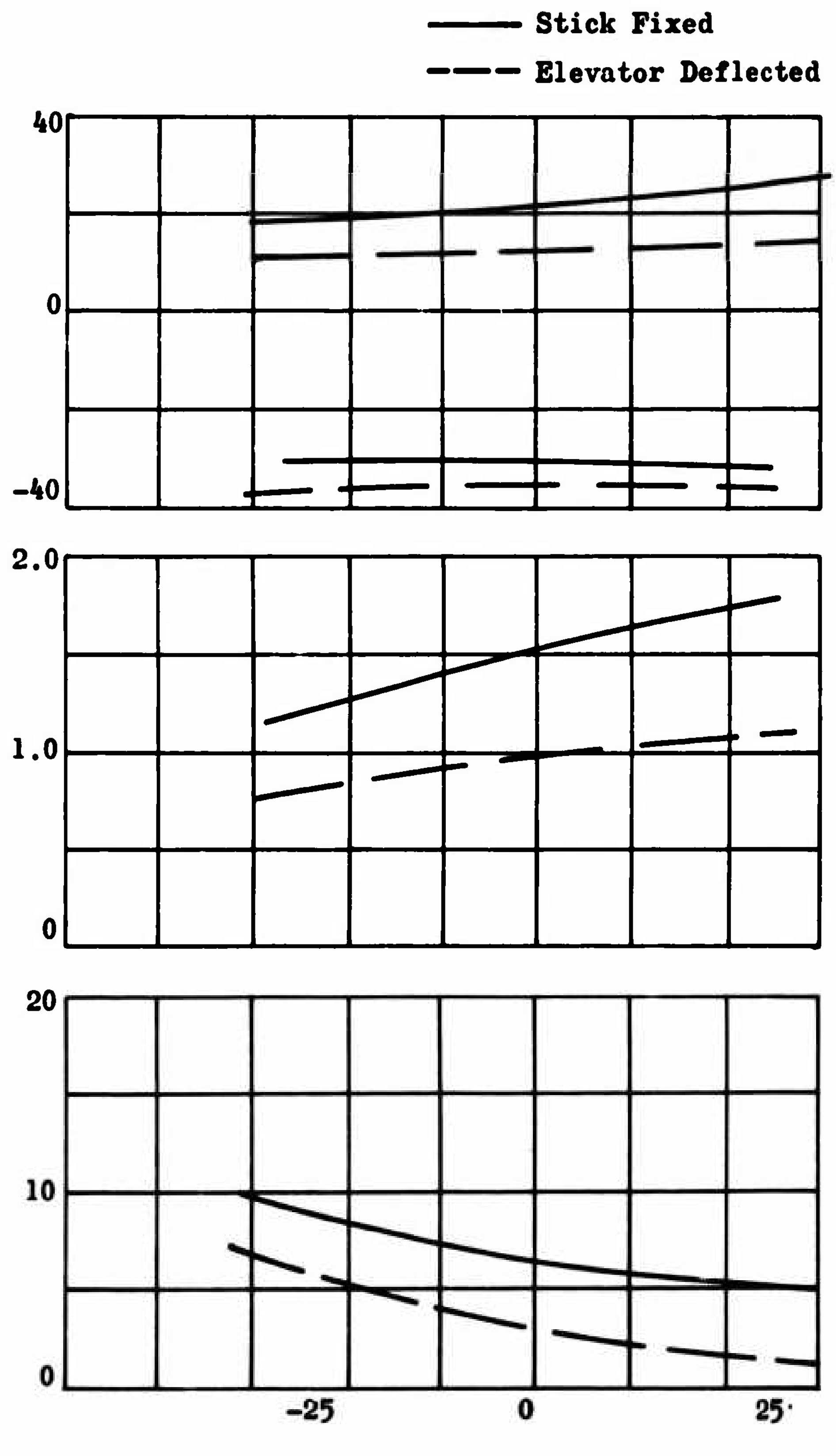
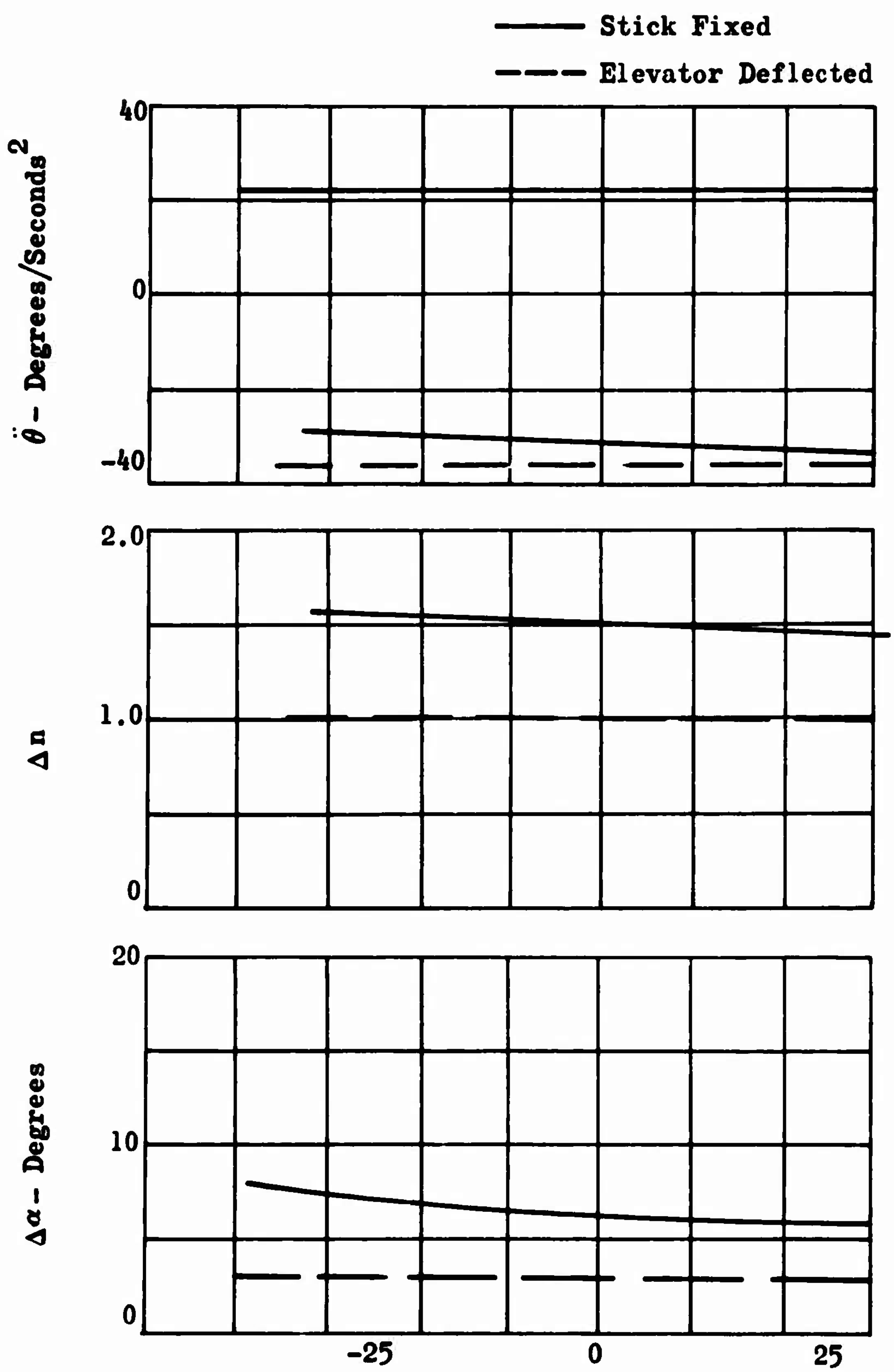


Figure 32 - Effect of Varying Lift



Relative Change in Pitching Moment - Percent

Figure 33 - Effect of Varying Pitching Moment

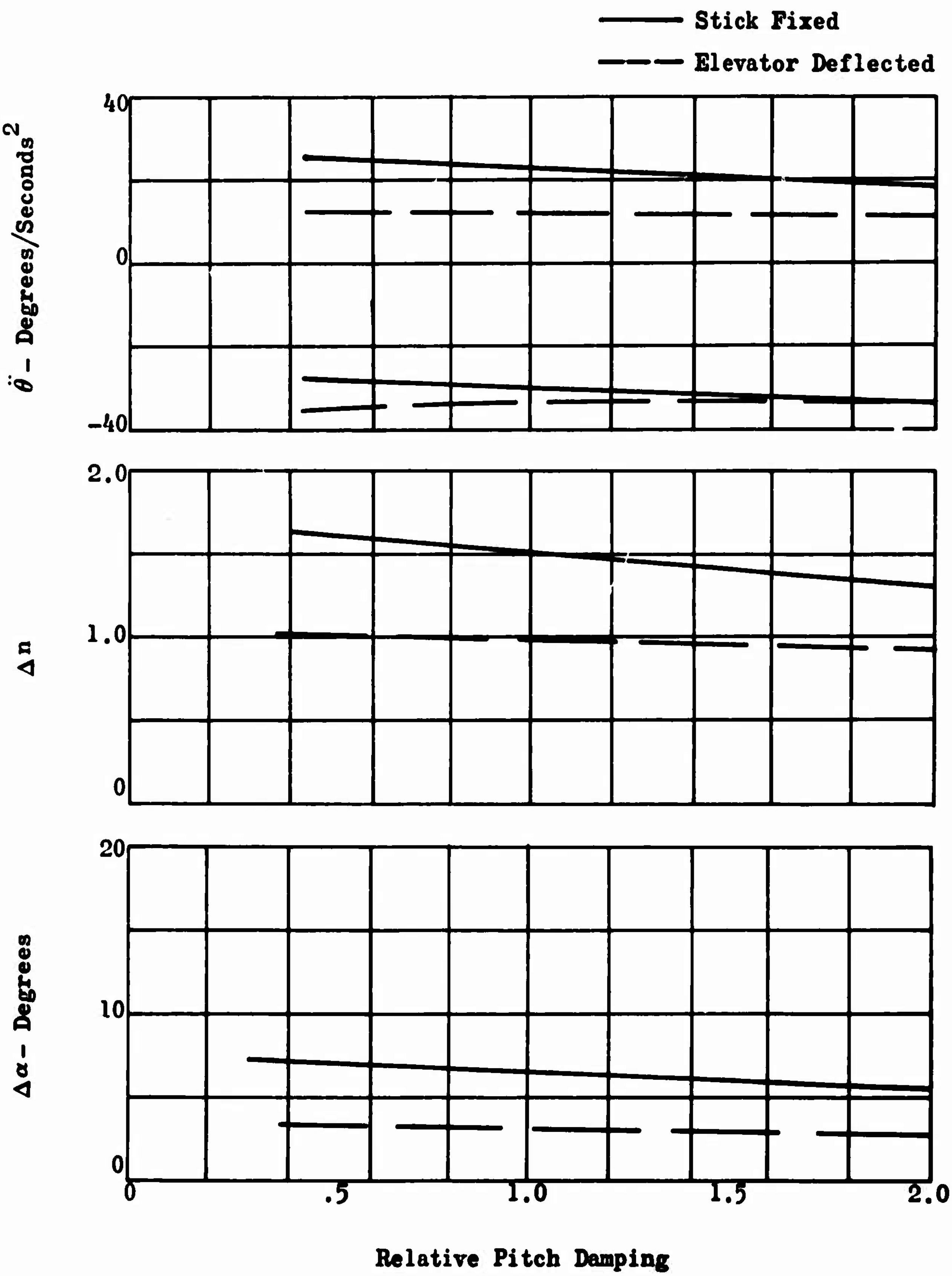


Figure 34 - Effect of Varying Relative Pitch Damping, $M_{\dot{\theta}}$

Cargo Extraction Acceleration

With the airplane flying at 140 knots, the 20,000-pound cargo was extracted at increasing levels of acceleration with each run. Figures 22 and 35 show the effects upon airplane response of this parameter. When the cargo was extracted at 0.5 g, there were large changes in most of the recorded quantities, and as the extraction acceleration increased, all these quantities decreased in magnitude when compared at the same time period. Cargo acceleration is one of the most significant parameters during the airdrop cycle. The θ, α_{FRL}, F_p, $\ddot{\theta}$, Δn, and M_c traces all show the marked effects of cargo acceleration.

The reversal in direction of the F_p trace caused by the Coriolis effect should be noted. Also noteworthy is the fact that corrective elevator favorably influences airplane response at all cargo accelerations. It would appear that a relatively high extraction acceleration is desirable in terms of minimizing airplane response.

The effect of increasing cargo acceleration on forward velocity is shown in Figure 22 to be minimal. It is concluded that the effect of forced ejection of cargo should be examined as necessary but that the effect on airplane response is overshadowed by the motions resulting from the sliding of the cargo and the loss of cargo weight.

Vertical Gust Effects

This study assumes a (1 - cos) type vertical gust which has a maximum vertical velocity of 25 feet per second. The wave length of the gust is the standard 25 mean-aerodynamic-chord lengths. The effects of the gust are seen in Figure 23. The time histories presented show the effects that result under the following four conditions: when no gusts exist and then when the aircraft is one-fourth, one-half, and three-fourths the way through a gust as the cargo package reaches the ramp door lip. Figures 23 and 36 show that the worst conditions occur between one-fourth and one-half way through the gust. At both of these conditions the limit load factor was exceeded for this particular airplane. The trace changed most at these two conditions which caused the vast increases in θ, Δn, M_c, and θ. The platform force, F_p, continued to increase in each of the four successive traces until the cargo left the airplane. Corrective elevator deflection provided relief of excessive response characteristics, particularly with regard to θ, Δh, Δn, and $\dot{\alpha}$. It is concluded that the relationship between cargo drop and distance into a gust has a significant effect on airplane response.

Elevator Rate

The effects of increasing the maximum rate of travel of the elevator are shown by Figure 37. The time history data show that even if the

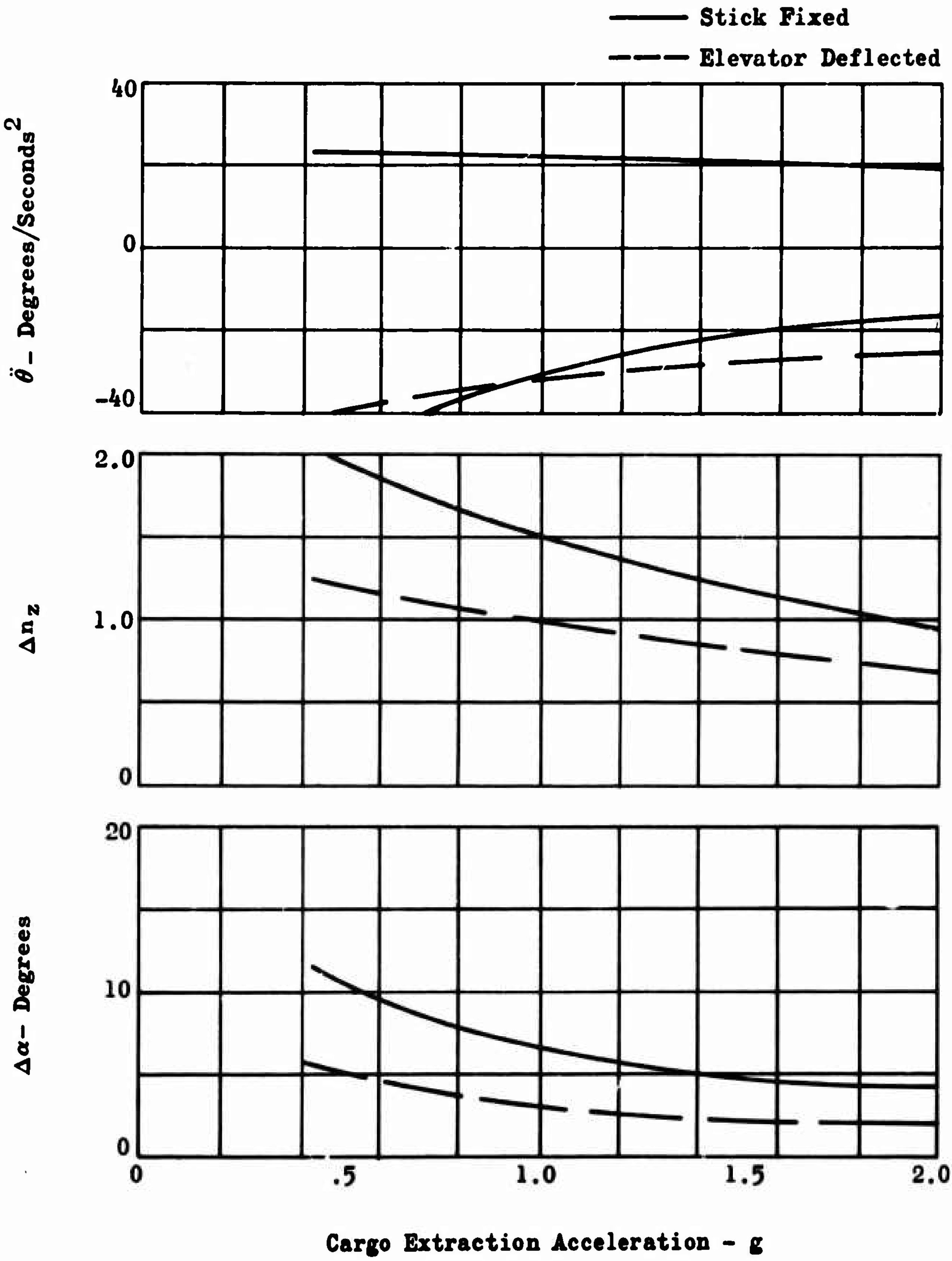


Figure 35 - Effect of Varying Cargo Extraction Acceleration

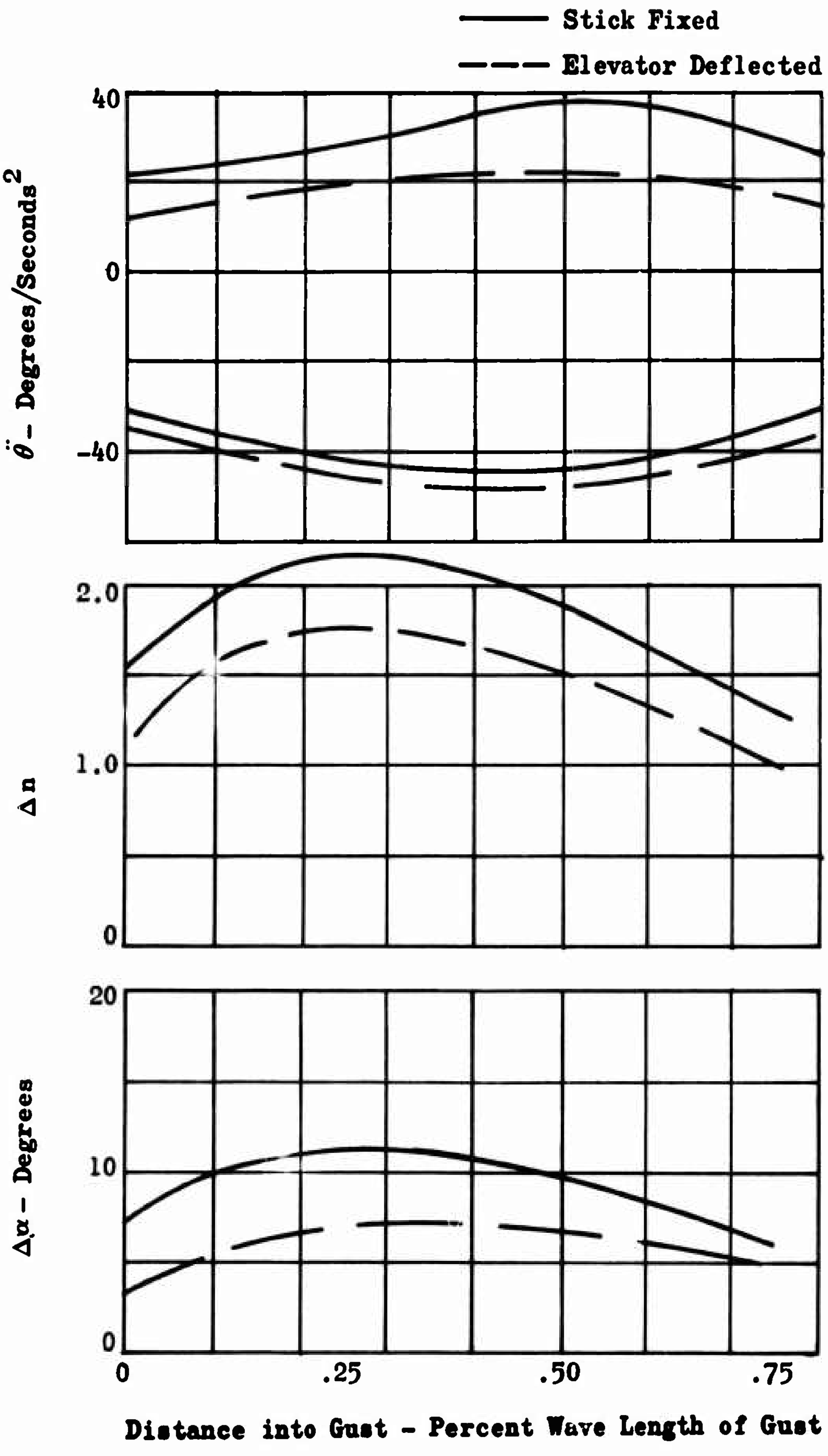


Figure 36 - Effect of Varying Cargo Drop in Terms of Distance into Gusts

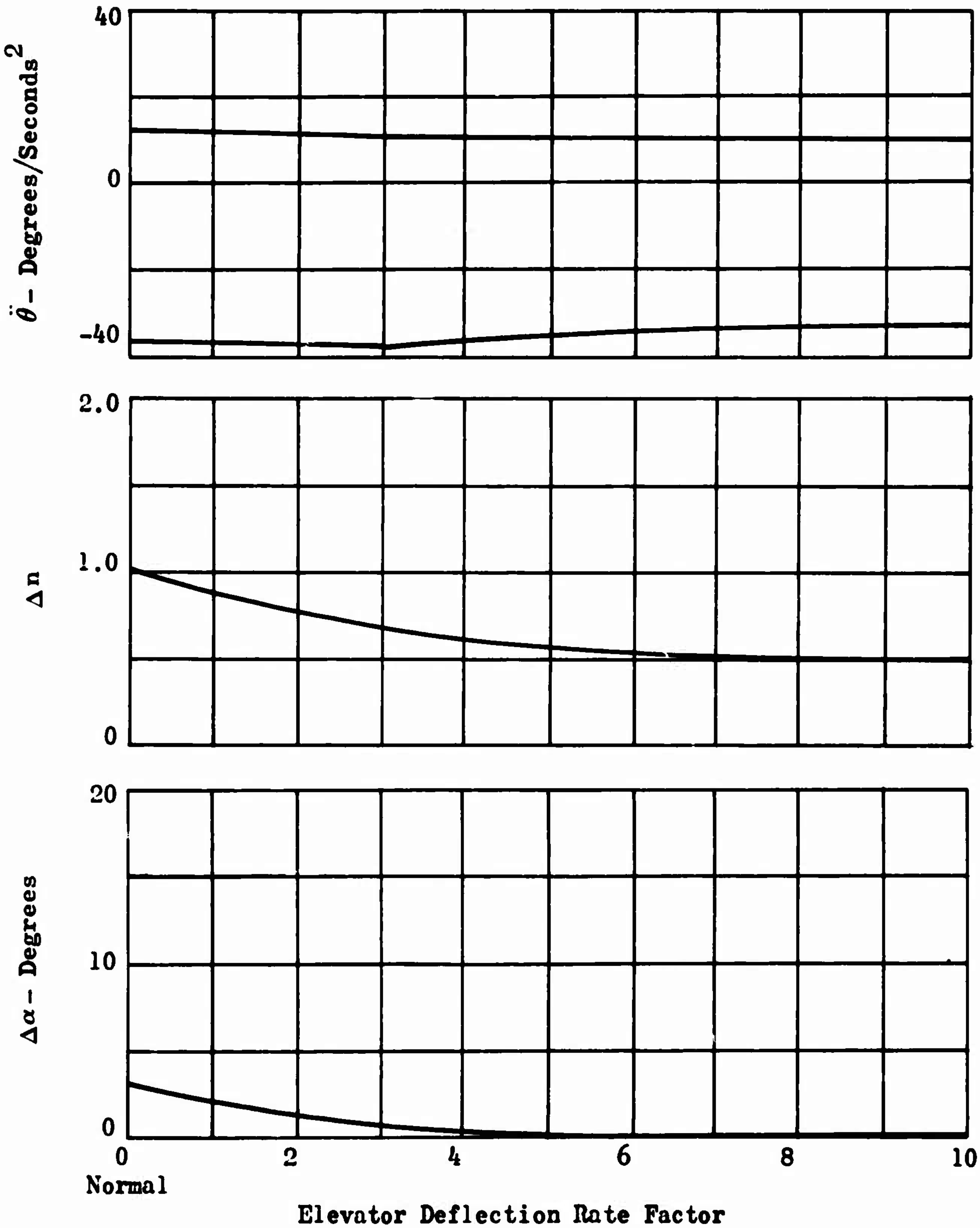


Figure 37 - Effect of Varying Elevator Rate

elevator rate is increased tenfold, not much is gained in the way of reducing the magnitude of the airplane response.

Multiple Drops

Figure 24 contrasts the airplane response to airdrop of a single 20,000-pound cargo package with that resulting from dropping three 10,000-pound packages. The time history data showed that when no corrective elevator deflection is applied, the multiple cargo drops extend the time over which all cargo leaves the airplane. This causes M_c to be extended over a longer period of time, thereby increasing the normal acceleration. From past experience, as confirmed by these traces, corrective elevator must be used if multiple drops are being made. Due to the multi-peaking of traces, no summary plot was made.

Forced Downward Ejection

Figure 25 shows the airplane response characteristics, both with and without corrective elevator deflection, when dropping the cargo package from directly beneath the airplane center of gravity. In this case, a 20,000-pound cargo weight was dropped at an airspeed of 140 knots. This downward ejection causes little change in response characteristics with or without corrective elevator, and the data were not cross-plotted.

Candidate Parameters for a Simulator

On the basis of the foregoing analysis, as evidenced by the time histories and cross-plots, it is considered that provision for variations in the following forcing parameters should be included in an airdrop delivery simulator.

- Cargo weight
- Airplane speed
- Center-of-gravity position
- Tip-off characteristics
- Extraction acceleration
- Pitch damping
- Gust effects
- Longitudinal control deflection and rate

A simulator should also include provision for simulating the following parameters:

- Lift
- Pitching moment
- Drag
- Thrust
- Airplane weight
- Airdrop altitude - both absolute and relative
- Airplane moment of inertia in pitch

PHASE III - SYSTEM CONCEPTUAL DESIGN

The primary purpose of the Phase III portion of the study was to give consideration to concepts for the form of the simulator based upon the results of Phase II. In order to establish the preliminary or conceptual system design, the following approach was taken:

- o Criteria and design considerations for simulator
- o Concepts for airdrop simulator
- o Application of criteria to concepts
- o Analysis of selected conceptual designs

CRITERIA AND DESIGN CONSIDERATIONS FOR SIMULATOR

The primary purpose of the proposed airdrop simulator is to reproduce or predict the response of the airplane resulting from airdrop of cargo by either current methods or those projected for use in the next 10 years. In the process of fulfilling this purpose, various criteria or design considerations must be established. The first criterion to be considered is that the system should provide complete simulation and, specifically, should be able to describe airplane motion adequately. Other criteria or design considerations such as cost, accuracy, simplicity, compatibility, reliability, adaptability, utility, and productivity must also be considered as factors determining conceptual design.

Accuracy

The simulator must accurately represent the response of an airplane to the airdrop, or forced ejection, of a cargo package. The initial determination of the simulator accuracy should be based upon comparison with known flight-test results.

Functional Reliability

The simulator should be capable of operation for extended periods of time in all-weather environment with minimal maintenance. The repeatability of test results is important in the utilization of the facility. The simulator should be capable of achieving a state of operability within a few hours after protracted periods of inactivity.

Simplicity

The simulator should be capable of operation with a minimum of personnel. The skill level should be compatible with that available

to the U. S. Army and, in particular, to USAAVLABS. Simplicity is also a key consideration in cost of development, cost of operation, and functional reliability.

Compatibility

The simulator should be adaptable to those airplanes currently in the U. S. Army inventory so that any proposed airdrop systems may be checked for compatibility with existing equipment. A minimum amount of labor and costs should accrue in preparing the simulator to receive all types of existing airplanes.

Adaptability

The simulator should be adaptable to future aircraft and airdrop systems for the time period 1965 to 1975. Accordingly, the simulator must have the inherent ability to extend the magnitude of significant or critical parameters. The capability to account for the possible addition of new parameters, which may assume importance in the future, should also be inherent in its design concepts.

Utility

The utility of a simulator is dependent upon the accessibility, availability, and the usefulness of the device for other functions. This quality must be related to the frequency of use of the simulator.

Productivity

This consideration relates to the rate of input and output of the simulator. Otherwise stated, the time should be a minimum from the decision to use the simulator until it is ready for the first run. The rapidity with which results are presented in a form ready for interpretation is also a key factor.

Costs

The simulator should be of minimum cost compatible with considerations of the foregoing criteria.

CONCEPTS FOR AIRDROP SIMULATOR

The contractor has examined many concepts that have application to an airdrop simulator. These concepts include such devices as rocket sled track, free-flight models, whirling arm tower, cockpit simulators, housed track-mounted models, analog and digital computers, jet-car sled, inclined track, and link-type trainers. Some of these systems show more promise than others. Some excel in one area of airdrop but cannot adequately cope with the broad scope of the airdrop problem. For example, the jet-car sled and the inclined track cannot simulate the airplane motion but would be excellent candidate concepts for investigating airdrop cargo dynamics. On the other hand, many of the above listed concepts can simulate airplane response, but such items as cost, reliability, accuracy, manpower, size and space, and instrumentation must be considered in determining the most feasible concept.

The possible concepts have been grouped into three categories for discussion as follows:

- Mechanical
- Electromechanical
- Electronic

Mechanical

The mechanical systems considered in this study for adaptation as an airdrop simulator included the powered-sled tracks, free-flight models, whirling arm tower, jet-car sled, inclined track, and the housed track-mounted model. All of these systems involve the use of scale models of the airplane. A brief description of the operational characteristics of each concept follows, and the advantages and disadvantages of each concept for use as an airdrop simulator are also presented.

Powered-Sled Track

A model can be mounted on a powered sled traveling on a track consisting of two parallel rails firmly seated in concrete. The carriage speed can be made to vary from 0 to about 250 knots. Such a facility can be used as an airdrop simulator but is impractical because of prohibitive construction and maintenance costs.

Free-Flight Models

A free-flight model can be constructed and instrumented so as to fly by radio control with the cargo extracted or ejected by remote control. However, factors such as model scaling effects, instrumentation, and time of model construction would tend to make this concept impractical.

Whirling-Arm Tower

This type of facility utilizes an "arm" rotating in a horizontal plane. A scale model, which can be released for free flight, is attached to the outer end of the rotating arm. During the period of free flight, the airplane's motion can be measured as a result of radio-impulsed cargo extraction. This type of simulation would have high operating cost because the models would be destroyed or damaged upon landing.

Another feature of this facility would be to measure airplane response resulting from cargo extraction without releasing the model from the whirling arm. Under these conditions extensive instrumentation requirements would tend to increase the cost of operation of the facility.

Jet-Car Sled

The jet-car sled consists of jet engines mounted on a rubber-tire vehicle which travels down a concrete runway guided by a slotted rail located in the middle of the runway. A facility of this nature cannot measure airplane response but could be used for cargo dynamic studies.

The Inclined Track

This facility, located at Wright-Patterson Air Force Base, was primarily designed to provide controlled environment testing associated with ground impact of parachuted vehicles, supplies, and equipment. Initially, the cargo is lifted into the upper end of the inclined track and placed on a carriage which travels down the incline and is released during the level portion of the track. This type of system does not lend itself to measuring airplane motion. Therefore, use as an airdrop simulator would not be practical.

The Housed Track-Mounted Model

The housed track-mounted model system is a facility similar to the Dynamic Model Track located at Princeton University and described in Reference 3. The function of this facility is to fly a dynamically similar model in an enclosed area and to follow the natural motions of the model with a slaved carriage, thereby providing a frame of reference for measuring the time histories of the model motion. This type of system could beneficially be adapted to the needs of an airdrop simulator.

Electromechanical

Link-Trainer Type

A Link-trainer-type device would incorporate both electronic and mechanical components coupled together. A fully instrumented free-rotating cockpit hydraulically operated would receive input signals from an electronic computer which computes the airplane motion. This type of system could be used effectively for training pilots, which is not the purpose of the subject airdrop simulator. However, since the essential component of this device is a computer, the device is rejected in favor of the computer itself.

Cockput Simulator

The cockpit simulator is a device similar to the Link trainer. The primary difference is that the flight station of the cockpit simulator is stationary. Therefore, this type device cannot adequately determine airplane response. However, it is conceivable that the time histories could be determined with the help of a computer as discussed in the previous paragraph.

Electronic

There are two types of electronic concepts for airdrop simulators - the digital computer and the analog computer. Each has its inherent advantages and disadvantages. Either computer can be an effective airdrop simulator by developing mathematical models that are programmed to represent the airplane and the airdrop system as required. The equations use as much factual data as possible, e.g., aerodynamic data derived from flight or wind tunnel test parachute drag data, or any theoretical data available, to aid in the simulation.

APPLICATION OF CRITERIA TO CONCEPTS

Some of the previously described criteria such as weight, adaptability, and productivity were applied to each concept in order to determine those concepts worthy of more detailed consideration. The evaluation is presented in summary form in Table II wherein each concept is rated. Three ratings are given: excellent, fair, and poor. A blank space under a criterion in Table II means the concept cannot possibly fulfill that function.

Of the concepts enumerated in Table II it appears that some are impractical while others cannot adequately provide the desired activities recommended for a simulator. All of those concepts which require the use of physical models suffer the following inherent disadvantages:

TABLE II

RATING OF SIMULATOR CONCEPTS

Concepts	Accuracy	Reliability	Simplicity	Compatibility	Adapt.	Cost	Access	Productivity
Powered-Sled Track	Poor	Fair	Poor	Poor	Poor	Poor	Poor	Poor
Free-Flight Models	Fair	Poor	Poor	Excel.	Excel.	Poor	Poor	Fair
Whirling-Arm Tower	Poor	Fair	Poor	Fair	Fair	Poor	Poor	Fair
Dynamic-Model Track	Fair	Fair	Fair	Excel.	Excel.	Poor	Fair	Fair
Jet-Car Sled	Poor	Fair	Poor	Poor	Poor	Poor	Poor	Poor
Inclined Track	Poor	Fair	Poor	-	-	Fair	-	-
Link-Type Trainer	Excel.	Excel.	Fair	Poor	Poor	Poor	Poor	Fair
Cockpit Simulator	Excel.	Excel.	Fair	Poor	Poor	Poor	Poor	Fair
Analog Computer	Excel.	Excel.	Excel.	Excel.	Excel.	Fair	Excel.	Excel.
Digital Computer	Excel.	Excel.	Excel.	Excel.	Excel.	Fair	Excel.	Poor

- o Must be built for each airplane to be investigated
- o Must be scaled in size, weight, and moment of inertia
- o Must have extraction/ejection capability
- o Present scaling problems of extraction systems
- o Require instrumentation and associated calibration
- o Pose model construction problems because of simulator speed requirements
- o Necessitate costly model construction due to tolerance required
- o Include scale effects in data output

The rocket sled track and whirling arm tower require building of costly facilities and, because of this, are rejected as possibilities. The jet-car sled, the inclined track, the Link trainer, and the cockpit simulator are discarded because these concepts do not lend themselves to determining airplane motion. However, the jet-car sled and the inclined track would be good concepts for a simulator determining cargo dynamics.

It is accordingly concluded that there are three concepts which can serve as airdrop simulators. These are: the dynamic model track, the digital computer, and the analog computer.

ANALYSIS OF SELECTED CONCEPTUAL DESIGNS

Dynamic Model Track

In order to pursue the feasibility of the dynamic model track, a visit was made to Princeton University for a detailed inspection of this U. S. Army-sponsored facility. Results of the visit indicated that a similar system could be designed and built for an airdrop simulator or that the facility at Princeton could be adapted to achieve the desired degree of simulation. However, certain technical considerations must be resolved which may render this system too costly.

The dynamic model track, discussed in detail in Reference 3, is an apparatus designed and built for research on the dynamic stability characteristics of aircraft at low speeds, 0 to 65 knots. This facility consists of a carriage mounted on a monorail track housed in a 7500-foot long building with a test section 35 feet high and 30 feet wide. Airplane models scaled to complete dynamic similitude are mounted on the carriage. Five degrees of freedom are possible.

Carriage performance is characterized by a maximum horizontal acceleration as high as 0.6 g. The maximum speed of the system is primarily limited by the carriage-track structure, and not by the installed power. Models tested on the track have weighed from 20 to 50 pounds.

The facility was designed primarily for testing helicopters and V/STOL airplanes in hovering and low-speed flight, a region where virtually no actual wind-tunnel test data existed. However, the airdrop simulator will be testing many different aerial delivery systems on an airplane on which aerodynamic data are readily available. Since these data exist, then a facility such as this would be superfluous because an electronic computer could produce accurate airplane response for a fraction of the cost in much less time. Also, through use of the computer the problem of scaling the model would not exist.

It appears that use of the dynamic model track would require 6 to 7 months preparation time for each new airplane or concept to be tested. The time is required to construct the model and to make calibration or checkout runs.

The present configuration of the facility does not meet the 250-miles per hour speed requirement for a simulator. Expansion of the facility to achieve this speed would, at a minimum, entail:

- Larger drive motor
- Increased braking system capability
- Use of smaller models in order to maintain constant Froude number

On the basis of the foregoing comments, it would appear that the use of the dynamic model track, while possible, is not as practical as a computer.

Computers

In addition to meeting all of the criteria postulated for a simulator, the computer automatically covers speeds ranging from 60 to 250 knots specified by virtue of the equations presented herein. In regard to speed, the computer will indeed cover the speed range from 0 to supersonic values provided the proper aerodynamic coefficients are utilized. This does not mean that the equations are adequate below 60 knots or above 250 knots,for appropriate V/STOL terms and high Mach number influences would have to be added to the equations. However, the capability is inherent in its concept.

A computer also adequately indicates the effects of cargo extraction or ejection regardless of the means employed. It does so through the values of cargo extraction acceleration which are an input to the program. As far as the structural effects are concerned, they may be calculated from the airplane response just as wing loads or tail loads are evolved from such terms as load factor. In any event, the structural effect of an airdrop could not exceed the design requirements of flight, ground, and crash conditions as defined in the general structural design specifications.

The digital computer can be used very effectively as an airdrop simulator. It has all the necessary attributes required to fulfill the requirements. However, when dealing with an investigation that demands time histories for a complete analysis, the digital computer is rather cumbersome when viewing the form of the output data. Much data, in the form of printed readout, is produced in a short period of time, but these data must be plotted to obtain the time history. The manhours involved here increase rapidly even if a form of X-Y plotter is available.

The analog computer is believed to be the best airdrop simulator when all the criteria are considered. The analog computer has the distinct advantage of being able to produce any number of time histories in visual form as computer or simulator output. Since this investigation led to the analog computer as the simulator, further study was conducted on such items as the type and amount of equipment, the space necessary to house the equipment, the environmental and power requirements, and the approximate cost for the complete installation.

Analog Computer

The procedure for solving problems on the analog computer consists of establishing relations between machine voltages and real time which are mathematically equivalent to the relations existing between the problem variables. The preparation of a problem, then, consists of designing this mathematical model. If the model is correctly designed, the equations which represent the relations between interconnected machine elements will be identical to the equations which describe the physical problem being simulated on the machine. The analog computer is essentially a collection of building blocks for constructing the mathematical model, along with an interconnection system which facilitates its construction. The building blocks are computer elements which perform the required mathematical operations, such as addition, multiplication by constant or variable, integration, function generation, or combinations of these operations.

The general procedure for preparing a given problem for solution may be divided into the following steps:

- Proper representation by mathematical equations
- Arrangement of equations for computer solution
- Wiring diagrams
- Adapt magnitude and range of parameters
- Input/output considerations

Performance of the system to be studied must first be represented by mathematical equations. Generally, there are a number of different ways of representing a given physical system mathematically, such as choice of coordinate systems, for example. For this reason, acquaintance with the physical problem is always desirable for the computer engineer, since one choice of equations may be more suitable for computer purposes than another. Furthermore, the computer is used to establish a model and the engineer's ability to visualize the actual behavior of the system within the model is dependent to a large extent on his acquaintance with the physical problem.

Once the equations are established, they are rearranged for computer solution. This rearrangement usually consists of solving for the highest order derivative in each equation, since the nature of the computer elements makes integration an easy and stable operation, while differentiation tends to be unstable.

Representation of the equations is shown by a "block diagram" in which computer elements are represented symbolically. This block diagram represents the equations pictorially and makes it easier to visualize particular features or difficulties which may be encountered. The block diagram shows the interconnection of the building blocks of the computer to simulate the equations being solved.

Scale factors are now selected. Scaling the problem essentially means substituting machine variables of voltage and real time for the problem variables. This may be done by:

- Actually transforming the problem equations to machine equations.

- Including a scale factor with each problem variable. The two methods are equivalent and both are illustrated in the following pages. Essentially, then, scaling a given problem for computer solution amounts to adapting the magnitude and range of variation of a given problem variable, to the total exclusion of 0 to 100 volts and a number of seconds, which are the computer variables.

Inputs and outputs to the computer must now be considered. Outputs can be represented by both meter readings (analog or digital), curves

drawn by direct writing oscillographs, or X-Y plotters. Arrangements can be made to provide results with a printer, electric typewriter, card punch, magnetic tape, or other forms of recording. The provision for these several means of output must be carefully considered in the block diagram and in the selection of scale factors, in order to take into account possible overloading of machine elements, space available on the patch board, and proper scales and magnitudes of the terms being recorded.

Inputs to the computer must come from aerodynamic data which describe the airplane characteristics. The equation of motion and the auxiliary equations require either a constant or the generation of a specific curve that will adequately describe that particular parameter. Table III shows a typical example of the calculations required for the constants and also shows the potentiometer number, the parameter it simulates, the numerical setting, and the input gain. It can be seen that when one or more parameters change, a new sheet should be completed because "bookkeeping" is essential.

Figure 38 shows a typical example of an aerodynamic curve and the mathematical manipulation required for the function generation of a nonlinear curve. (A tabulation of these data is shown in Table IV). Each parameter in the equation of the mathematical model having non-linear properties will require similar calculations.

The time required to program the input data and check out the analog preparatory to performing simulation runs would be three weeks. Inasmuch as the analog works in real time and supplies a time history as an output, the computer time required per run is on the order of 8 to 10 seconds. However, the actual time required to complete a series of runs is considered to average about 10 minutes per run on the basis of the Phase II work.

Analog Computer Size and Type - The Phase II study in fact did essentially use the analog computer as an airdrop simulator. The machine elements used in the parametric study have been previously shown in block diagram form. They were properly arranged to represent adequately the equations of motion of the airplane and the auxiliary equations for input. These wiring diagrams contain the type and amount of analog equipment used. A list of the Phase II equipment is given below for reference:

41 summer amplifiers

10 integrators

57 potentiometers

3 function generators

17 multiplier-dividers

3 manual switches

3 resolvers

2 electronic switches

2 limiters

1 comparator

2 relays

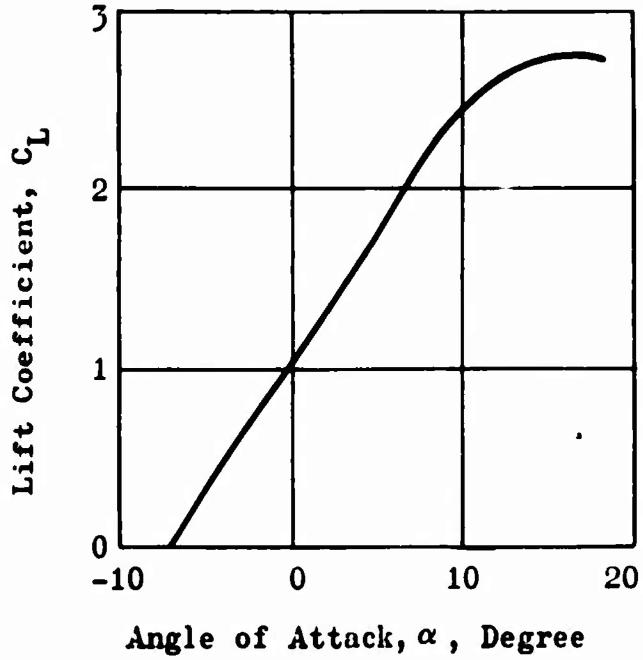
TABLE III

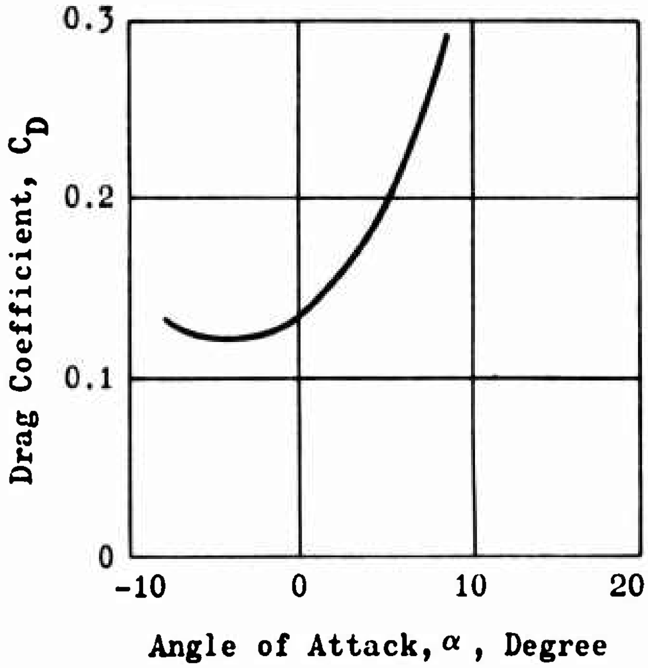
SERVO-SET COEFFICIENT POTENTIOMETER AND INPUT GAIN SETTINGS

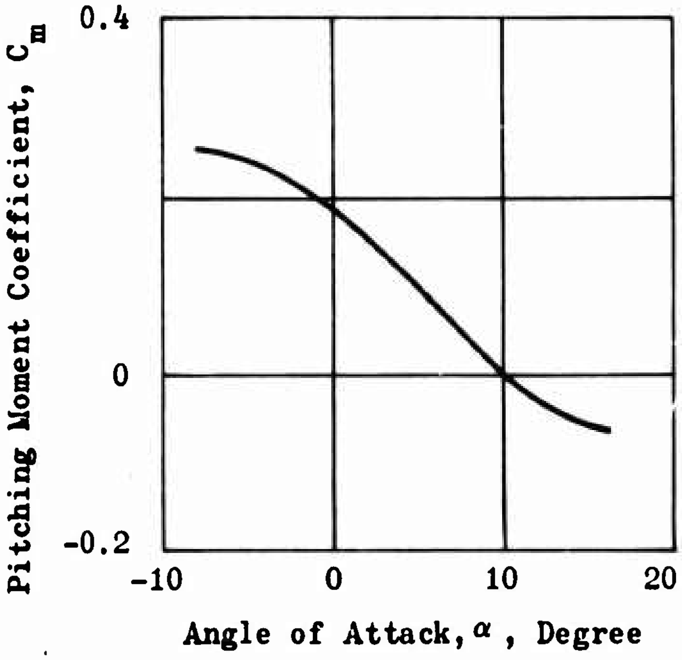
Potentiometer Number	Parameter	Potentiometer Setting	Gain
01	$W_a/10^5$	1.0000	1
02	2.0	0.2000	10
03	1/2	0.5000	1
05	(1/1.69)(2)	0.1183	10
06	$W_a/2 \times 10^5$	0.5000	1
07	180/20	0.9000	10
10	1/2	0.5000	1
12	g/50	0.6450	1
13	180/20	0.9000	10
15	$m_c/10^3$	0.6210	1
16	2.0	0.2000	10
17	5.0	0.5000	10
24	$C_L, f(\alpha)$ S.F.	1.0000	1
25	$C_{L_{\delta_T}}/5$	0.0186	1
26	$400/m_a$	0.1288	1
28	$\rho S/3.2$	0.1300	10
29	$\bar{c}/10$	0.1370	10
36	$T_1/10^5$	0.2000	1
39	$C_{m_{\dot{\alpha}}}/100$	0.1365	1
41	1/10	0.1000	1
42	$C_{m_{\delta_T}}/5$	0.0598	1
43	$2 \times 10^4 z_e/I_{y_a}$	0.0416	1
44	$5 \times 10^5/I_y$	0.5000	1
45	20/180	0.1111	1
46	$(x_{c.g.} - x_c)/50$	0.0000	
49	57.3/20	0.2865	10

TABLE III (continued)

Potentiometer Number	Parameter	Potentiometer Setting	Gain
51	$x_c/50$	0.8560	1
63	57.3/20	0.2865	10
66	5.0	0.5000	10
67	57.3/20	0.2865	10
70	$\ddot{x}_c/100$	0.3220	1
71	2.0	0.2000	10
101	$200/m_a$	0.0640	1
102	$U_o/500$	0.4750	1
103	57.3/180	0.3183	1
105	1/2	0.5000	1
106	1/4	0.2500	1
124	$C_{L_{\delta_e}}/5$	0.0954	1
125	$10^5/W_a$	1.0000	1
129	10.0	1.0000	10
139	$C_{m_q}/100$	0.2710	1
140	$\bar{c}/10$	0.1370	10
141	$C_{m_{\delta_e}}/5$	0.3050	1
142	$\bar{x}/\bar{c}$	0.0600	1
143	$4x10^6/I_{y_a}$	0.4170	10







<u>NOTE</u>
A tabulation of aerodynamic data calculated for function generator is shown in Table IV on page 105.

Figure 38 - Airplane Aerodynamic Data Calculated for Setting of Function Generator

TABLE IV

TABULATION OF AERODYNAMIC DATA CALCULATED FOR FUNCTION GENERATOR

α	C_L	C_D	C_m	/20	$C_L/5$	$C_D/0.5$	$C_m/0.5$
-8	-0.140	0.131	0.256	-0.4	-0.028	0.262	-0.512
-4	0.450	0.122	0.231	-0.2	0.090	0.244	-0.462
0	1.035	0.134	0.185	0	0.207	0.269	-0.370
4	1.615	0.177	0.118	0.2	0.323	0.354	-0.236
8	2.180	0.267	0.026	0.4	0.436	0.534	-0.052
12	2.550	0.400	-0.035	0.6	0.510	0.800	0.070
16	2.720	0.400	-0.063	0.8	0.544	0.800	0.126

This list is considered to be the minimum analog equipment necessary for adaptation as airdrop simulator. However, in order to provide the most efficient and up-to-date components adaptable to any airdrop system projected for 1965-75, the following components are recommended:

- o Solid state type
- o Equipment components
  - 80 summer amplifiers
  - 24 integrators
  - 100 servo-set potentiometers
  - 15 function generators
  - 30 multiplier-dividers
  - 10 manual switches
  - 5 resolvers
  - 5 limiters
  - 2 X-Y plotters
  - 1 8-channel strip-chart curvilinear recorder
  - Patchable logic
  - 6 comparators
  - 6 electronic switches
  - 12 relays with driver-amplifiers
  - 12 or/nor (and/nand) gates
  - 6 Schmitt triggers
  - 6 RST flip-flop reset set triggers
  - Digital input-output and control
- o Specifications
  - Operators console with electronic mode control and $\pm$ 100 volt reference supply

A. Type - A solid state analog computer is an all-transistorized model which is considered the best and most efficient for the following reasons:

- o Low maintenance cost as compared to the tube type
- o Less heat generation
- o Lower air-conditioning requirements
- o Smaller space

B. <u>Equipment</u> - In the process of arriving at the amount of analog equipment necessary for an airdrop simulator, use was made of the existing programs at the contractor's facility as well as those resulting from the Phase II study. A comparison of the equipment used in Phase II with the recommended components shows that the minimum amount of equipment is approximately 50 percent of the maximum equipment. However, the suggested additional equipment will greatly facilitate the simulation of airdrop systems expected in the 1965-75 period. The patchable logic gives the computer the ability to make certain types of decisions, and the digital input-ouput and control will help reduce initial input human errors. It greatly speeds the process of changing problems or run conditions.

C. <u>Specifications</u> - The operator's console integrates all the equipment necessary to operate the machine. This control cabinet housing consists of the manually set potentiometers, manual switches, patchable logic, and electronic mode control. The electronic mode control consists of push buttons electronically operated to control the computer.

<u>Cost and Physical Considerations</u> - The previously outlined analog equipment will require:

- Initial cost of $350,000
- Electrical power for operation, 20 KVA
- Room measuring 20 feet by 20 feet
- Six-ton air conditioner
- Services of an electronic technician for maintenance
- Services of a full-time programmer during operation
- Operating cost of $13 per hour. (Cost includes programmer and overhead but does not include part time cost of maintenance or cost of the engineer who requested simulation.)

These data are a composite ıs derived from information supplied by three computer manufacturers.

By way of contrast, analog computer time could be purchased by USAAVLABS from private contractors, academic institutions, etc. for about $25 per hour. Hence, the initial purchase price, not counting maintenance and operating costs, would buy 14,000 hours of analog computer time. This analog time is roughly equivalent to the complete investigation of 100 different airdrop systems. This estimate is based upon three weeks' set-up time per system plus the 64 runs required per system as discussed in the following paragraphs:

Digital Computer

The equations of motion presented in this report can be programmed for solution on any digital computer including the model currently in use by USAAVLABS. It is considered that a competent programmer would require three weeks to program and check out the equations. It is considered that three weeks would be required to prepare the necessary input data for each series of simulated airplane responses to an airdrop.

The model of the computer currently available at USAAVLABS would require approximately 10 minutes to make each run. In addition, the X-Y plotter available at USAAVLABS would probably require about 20 minutes per run to plot the printed read-out data. This makes a total of about 30 minutes that is required to produce a plotted time history of a simulated response for one flight condition.

For purposes of comparison, assume that an airdrop system adaptable to an airplane in the Army inventory is to be evaluated. It will be assumed that the following parameters will be varied in magnitude with a minimum of four values each:

- Cargo weight
- Initial airplane velocity
- Airplane center of gravity position
- Cargo tip-off characteristics
- Extraction acceleration
- Vertical gust
- Extraction cable angle
- Cargo sliding distances

For these eight parameters, with each having four different values, 32 flight conditions will hence be required for proper evaluation. It is recommended that all 32 flight conditions be made both with and without corrective control deflection. Therefore, the total number of actual runs that will adequately evaluate an airdrop system is 64 for each airplane or each airdrop technique. USAAVLABS has stated that four types of airplanes and seven different airdrop techniques are currently awaiting potential evaluation. Each of these 28 systems will have 64 computer runs making a total of 1792 runs. It takes the current USAAVLABS computer approximately 10 minutes to compute each run. Therefore, nearly eight weeks of computer time, exclusive of X-Y plotter time, would be required each year to evaluate the 28 systems.

The computer currently being used by USAAVLABS at Ft. Eustis is operated about 70 percent of the regular work week. This usage requires about 37 weeks per year which means that the current USAAVLABS computer has the time available for use as an airdrop simulator. Costs of operation were estimated at $35 per hour.

At the rate of 30 minutes' total time per run, 23 weeks would be required to obtain complete time histories. Assuming that the equations are programmed, and allowing three weeks' set-up time for each airplane, the total investigative time would be 35 weeks. This, of course, presumes that the characteristics of the airdrop system, a necessary input to the computer, is available from other computer programs. The total computer cost including X-Y plotter is estimated to be on the order of $32,000. Assuming the analog is available or that an analog operation is contracted to a private contractor, the comparable analog cost would be about $23,000.

As previously stated, the time to complete an analog run is also 10 minutes; and the programming and set up time is the same as that of the digital computer. Therefore, the primary difference in the time aspects between the analog and the current USAAVLABS digital computer is the plotting time.

CONCLUSIONS

The results of this study led to the following conclusions:

1. The development of a laboratory apparatus that will adequately simulate the response of an airplane to the airdrop of cargo is technically feasible.

2. An extensive literature-patent search indicates that no airdrop delivery simulator apparatus exists per se, but it is believed that the Dynamic Model Track located at Princeton University could be adapted for use.

3. An airdrop simulator should include provisions for simulating the following parameters:

    - Cargo weight
    - Airplane speed
    - Center of gravity position
    - Tip-off characteristics
    - Extraction acceleration
    - Pitch damping
    - Airdrop altitude
    - Airplane moment of inertia in pitch
    - Gust effects
    - Longitudinal control deflection and rate
    - Lift
    - Pitching moment
    - Drag
    - Thrust
    - Airplane weight

4. The best simulator is an analog computer in that it fulfills all the criteria and requirements. It has the further advantage, as do all computers, of being capable of performing other computational functions when not being used as a simulator. While the analog computer is adjudged to fulfill all requirements and permits instantaneous interpretation of results by virtue of its output in the form of time histories, the current digital computer at USAAVLABS is adequate for the task when used in conjunction with an X-Y plotter.

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In addition to the above documents, 64 Lockheed-Georgia Reports were examined for material related to the study.

APPENDIX

LITERATURE AND PATENT SEARCH

The results of the literature search for information relating to items possibly applicable to this study are presented in this appendix. The search encompassed applicable ground devices and associated fields. A bibliography of the literature survey is listed along with appropriate abstracts of those items of significance.

Abstracts

1. "The Princeton Dynamic Model Track," H. C. Curtiss, Jr., W. F. Putman, J. J. Traybar, AIAA Aerodynamics Testing Conference, Washington, D. C., March 9-10, 1964, pp 33-41. The Princeton Dynamic Model Track is an apparatus designed and built for research on the dynamic stability characteristics of aircraft at low speeds, 0 to 65 knots. This facility consists of a carriage mounted on a monorail track housed in a 7500-foot building. Models, scaled to complete dynamic similitude, are mounted on the carriage. Five degrees of freedom are possible. Carriage performance is characterized by a maximum horizontal acceleration as high as 0.6g. The maximum speed of the system is primarily limited by the carriage-track structure, and not by the installed power. Models tested on the track have weighed from 20 to 50 pounds.

2. "Aerodynamics Testing on Rocket Sled Tracks," W. J. Strange, AIAA Aerodynamics Testing Conference, Washington, D. C., March 9-10, 1964, pp 189-195. This supersonic test facility provides 4.1 miles of precision-aligned two-rail track and is used for captive testing or rockets, guided missiles, aircraft, and their components. Weights in excess of 100,000 pounds have been accelerated to speeds as high as 400 knots. Low performance requirements are met by use of general-purpose sleds. The facility is fully instrumented, including framing cameras with speeds up to 16,000 pictures per second and FM/FM frequency-multiplexed telemetry system with 16 channels available for recording information.

3. "Aerial Delivery Test Facilities at QMFCIAF," Article 12, E. F. Williams, Activities Report 8, Quartermaster Food and Container Institute of the Air Force, July 1956, pp 149-154. This is an experimental airdrop facility whose primary purpose is to study load system aerial delivery problems.

Solutions to problems of impact damage to air-delivered supplies are investigated. These simulated airdrop packages are dropped from heights of up to 60 feet upon a concrete impact surface.

4. "All American Test Facility," The All American Word, All American Engineering Company, Wilmington, Delaware, July 1962. This facility consists of two 5000-foot runways equipped with slots into which are extended center-line guide blades on the underside of a dolly. Weights of the dolly vary from 50,000 (one carriage) to 400,000 pounds (three carriages fully loaded). Speeds of up to 114 knots have been attained.

5. "Inclined Test Facility," United States Air Force Parachute Handbook, WADC TR 55-265, Wright Air Development Center, Wright-Patterson Air Force Base, Ohio, December 1956, pp 8-2-20 and 21. The inclined test facility erected at WADC is used to simulate the conditions to which cargo platforms and other heavy aerial delivery equipment are subjected upon landing. Drop tests, combining vertical and horizontal velocities, can be made at weights of from 500 pounds to 25,000 pounds. This facility has a capability to simulate vertical velocities of up to 40 feet per second and horizontal velocities of from 10 to 60 feet per second. One end of the facility is inclined at an angle of approximately 22 degrees. The overall length is 380 feet, and its highest point above the ground is 90 feet. The drop zone or impact area is approximately 100 feet long by 50 feet wide.

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13. ABSTRACT

The contractor has performed investigations, research, and engineering for the purpose of ascertaining the technical feasibility of a laboratory apparatus capable of simulating the response of an airplane to an airdrop. The airplanes considered encompass those currently in use by the U. S. Army as well as those projected into the 1975 time period. Airdrops by means of aft extraction, gravity drop, and forced downward ejection were included in the analysis.

Results of the various phases have led to the conclusion that a simulator is feasible, but that no specifically applicable apparatus exists which is capable of performing adequate simulations without considerable modification. The results have indicated those parameters in, and as a result of, an airdrop which must be included in a simulation device. It is additionally concluded that the most practical device which best meets the criteria and system requirements established for a simulator is an analog computer. Although a digital computer could perform as a simulator, it would have the disadvantage of not providing direct reading time histories as would an analog device. Finally, it is concluded that the computer available at USAAVLABS is capable of performing adequate simulations.

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